

**Dynamics and Control of SEDSAT
Tethered Multi-Probe for Thermospheric Research
Flight Data Analysis of SEDS-II Satellite**

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Tethered Systems Dynamics and Flight Data Analysis

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SUMMARY

This report covers the three topics summarized in the following:

1) Dynamics and Control of SEDSAT

The orbital mechanics underlying the sling-shot technique, utilized by SEDSAT for its orbital transfer is analyzed. Then, simplified expressions for the satellite lifetime are provided in order to compute the minimum injection velocity to reach the required orbit. A control law is, then, developed for the deployment of SEDSAT on a 20-km-long tether by using the Small Expendable Deployment System. Finally, the robustness of the control law with respect to the variability of the deployer's model parameters is investigated in order to estimate the errors affecting the injection velocity at satellite release.

2) Tethered Multi-Probe for Thermospheric Research

Three papers, presented at the Fourth International Conference on Tethers in Space, are included in this report: (1) the first paper focuses on the chemical processes responsible for the cooling of the lower thermosphere as an effect of an increased concentration of "greenhouse gases" in the troposphere; (2) the second paper deals with the instrumentation required for measuring these cooling processes; and (3) the third paper focuses primarily on the dynamics and thermal requirements of a dual-probe tethered system deployed into the Earth's lower thermosphere for carrying out those measurements in order to prove the feasibility of such mission with present day tether technology.

3) Analysis of SEDS-II Flight Data

A paper, presented at the Fourth International Conference on Tethers in Space, is included in this report to illustrate the results of the analysis of the acceleration levels and dynamic noise on the SEDS-II end-mass.

1.0 DYNAMICS AND CONTROL OF SEDSAT

1.1 INTRODUCTION

The satellite SEDSAT, built by a team of students of the University of Alabama at Huntsville, will be injected into a higher orbit from the Space Shuttle in July 1997 by using a 20-km-long librating tether acting as a sling shot. Since the satellite is expected to have a lifetime of about 3 years, without reboosting, the height and eccentricity of the final orbit are a primary concern. The injection velocity (ΔV) at the satellite release must be maximized in order to maximize the apogee height of the final orbit and consequently the satellite lifetime. Moreover, the final orbit must be as insensitive as possible to variations of the deployer's friction parameters in order to provide an accurate orbital transfer of the payload. Consequently, the magnitude, direction, and timing of the ΔV at satellite release (i.e., when the tether crosses the local vertical and the tether is cut from the Shuttle) must be accurate and as insensitive as possible to variations of the model parameters. A non-linear control law (feedforward-feedback) for driving the satellite to the desired position with the right velocity at the end of deployment was successfully tested during the flight of SEDS-II in March 1994. However, differently from SEDS-II, the deployment of SEDSAT occurs mostly at libration angles greater than 45° and, consequently, the stability of the deployment maneuver must be taken into account. As explained better in the following sections the control strategy of SEDSAT is substantially different from the control strategy of SEDS-II.

1.2 Orbital Injection

The ΔV imparted by a librating tether can be simply computed by utilizing the well-known Hill's equations describing the motion of a mass with respect to an orbiting reference frame on a circular orbit where the z-axis is the ascending local vertical (LV) and the x-axis is along the local horizontal (LH) towards the flight direction. We restrict our analysis to the two-dimensional case only for the sake of simplicity (the extension to a three-dimensional case is readily done but it is not necessary for our discussion):

$$\begin{aligned}\ddot{x} + 2\Omega\dot{z} &= F_x/m \\ \ddot{z} - 2\Omega\dot{x} - 3\Omega^2 z &= F_z/m\end{aligned}\tag{1}$$

For null external perturbation, i.e., $F_x = F_z = 0$, the solution of eqns. (1) is as follows [1]:

$$x(t) = (2\dot{z}_0/\Omega)\cos(\Omega t) + (4\dot{x}_0/\Omega + 6z_0)\sin(\Omega t) + (x_0 - 2\dot{z}_0/\Omega) - (3\dot{x}_0 + 6\Omega z_0)t \quad (2.1)$$

$$z(t) = (\dot{z}_0/\Omega)\sin(\Omega t) - (2\dot{x}_0/\Omega + 3z_0)\cos(\Omega t) + (2\dot{x}_0/\Omega + 4z_0) \quad (2.2)$$

For a payload released at LV from a librating tether, whereby $\dot{z}_0 = x_0 = 0$, eqns. (2.2) yields:

$$z = -(2\dot{x}_0/\Omega + 3z_0)\cos(\Omega t) + 2\dot{x}_0/\Omega + 4z_0 \quad (3)$$

which for $\Omega t = \pi$ (i.e., half an orbit later) becomes

$$z_{\Omega t=\pi} = 7z_0 + 4\dot{x}_0/\Omega \quad (4)$$

The first term on the right hand side of eqn. (4) depends on the separation between the released satellite and the mother platform located at the origin of the coordinate frame while the second term depends upon the relative velocity at release as seen from the rotating observer. Equation (4) can be readily converted to polar coordinates L and θ where L is the tether length and θ the in-plane libration angle with respect to LV to yield (see Fig. 1)

$$\Delta H_{CM} = [7 \pm 4\sqrt{3} \sin(\bar{\theta})] L_{CM} \quad (5.1)$$

where we used the analytical expression for the maximum angular rate (at LV) of a freely-librating gravity-gradient pendulum with large amplitudes $\bar{\theta}$, i.e., $\dot{\theta}_{LV} = \sin(\bar{\theta})\sqrt{3}\Omega$. In eqn. (5.1) $z_{\Omega t=\pi}$ has been replaced by ΔH_{CM} which is more reminiscent of its physical meaning, that is, the height difference between the orbit of the mother platform (circular for the time being) and the apogee height of the center of mass (CM) of the released body. The reference to the center of mass will become particularly useful when dealing with an extended body like a satellite with an attached *massive* tether. The plus and minus signs, in eqn. (5), are for prograde and retrograde librations, respectively.

Equation (5.1) can be rewritten as follows

$$\Delta H_{CM} = (7\Omega L_{CM} \pm 4\Delta V_{swing})/\Omega \quad (5.2)$$

where $L_{CM}\Omega$ is the contribution (sometimes called the *hanging* component for tether satellites) associated with the rotational motion of the orbiting frame and

$\Delta V_{swing} = \sqrt{3}\Omega \sin(\bar{\theta}) L_{CM}$ (sometimes called the *swinging* component) is the contribution associated with the libratory motion of the system with respect to the same reference frame.

If conservation of energy and angular momentum are utilized instead of the simplified Hill's equations, then, eqns. (5) are replaced by the more accurate formula:

$$\Delta H_{CM} = \frac{v_p^2 \cdot r_p - \mu}{\mu / r_p - v_p^2 / 2} + L_{CM} \quad (6.1)$$

where the perigee velocity of the CM of the released body is

$$v_p = \sqrt{\mu / R_0} + \Delta V \quad (6.2)$$

In eqns. (6), μ is the Earth's gravitational constant, R_0 the semi-major axis of the orbit of the mother platform (here assumed circular but readily extendible to the elliptical case), and r_p the perigee radius of the released object CM.

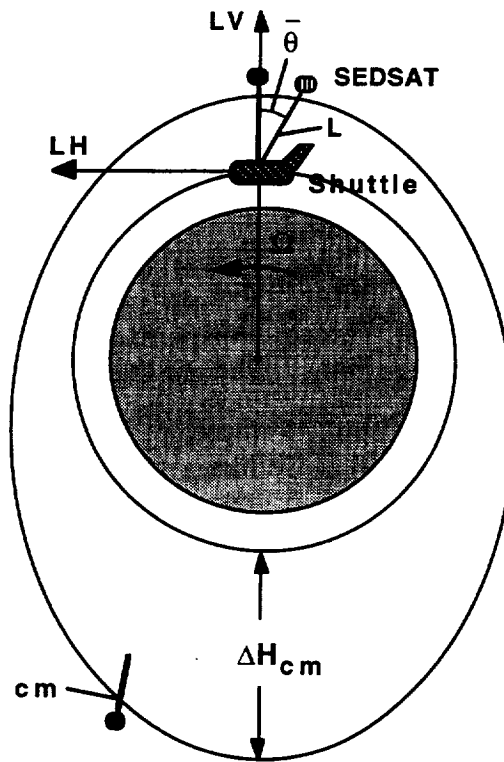


Fig. 1. SEDSAT system and reference frames

Equation (5.1) can be generalized (the derivation is not shown here for the sake of brevity) to the release from apoaxis of an initial orbit with small eccentricity e as follows

$$\Delta H_{CM} = [7 \pm 4\sqrt{3} \sin(\bar{\theta}) \pm 8e] L_{CM} \quad (7)$$

where, in this case, ΔH_{CM} is the height difference between the apoaxis of the initial orbit and the opposite apoaxis (i.e., with a π -rad phase difference) of the orbit after release. The plus and minus signs in front of the eccentricity-related term are for a release at periaxis and apoaxis respectively. Let us analyze, for example, the case of a release at apoaxis and compare a circular and eccentric initial orbits with equal energy (i.e., $R = a$ or radius of circular orbit = semi-major axis of eccentric orbit). Clearly, the eccentricity has two opposite effects: (1) on the one hand the apogee height of the eccentric orbit is higher than the equal-energy circular orbit by the quantity $h = eR$; (2) on the other hand the height difference after release ΔH_{CM} for an eccentric orbit is reduced by the quantity $8eL_{CM}$ with respect to the ΔH_{CM} for a release from a circular orbit. Since $8L_{CM} \ll R$, for almost any conceivable tethered system, there is a net gain in the altitude of the final orbit for a release from the apogee of an eccentric initial orbit when compared to the release from an equal-energy circular orbit.

Let us now go back to eqn. (5.1) with the plus sign which, in the current orbit scenario, applies to the release of SEDSAT from the Shuttle on a circular orbit. The height accuracy of the final orbit depends on L_{CM} and $\bar{\theta}$ but, while it is straight forward to provide a relatively accurate value for the tether length at the end of deployment, it is rather challenging to achieve an accurate maximum libration angle at release $\bar{\theta}$ with a passive deployer like SEDS [2-3] (i.e., a deployer that cannot reel in the tether and, more importantly, control the tether speed directly). From eqn. (5.1), the sensitivity of ΔH_{CM} with respect to variations of $\bar{\theta}$ and L_{CM} is as follows:

$$\partial \Delta H_{CM} = \pm 4\sqrt{3} L_{CM} \cos(\bar{\theta}) \partial \bar{\theta} + [7 \pm 4\sqrt{3} \cos(\bar{\theta})] \partial L_{CM} \quad (8)$$

Clearly, the sensitivity is smaller for large values of $\bar{\theta}$ which is desirable because large values of $\bar{\theta}$ are required for achieving high final orbits.

1.3 SEDSAT Orbital Lifetime

The SEDSAT satellite has a requirement of a 3-year lifetime without reboosting once it is detached from its tether. As explained later on, the tether will be cut twice: the first

time at the Shuttle end in order to raise the apogee of its orbit after release and the second time at the satellite end, close to apogee, in order to raise the perigee of its final orbit.

Estimating lifetime a few years ahead of a long-duration space mission is always subject to large errors because of the variability of the atmospheric density, which is particularly strong at the orbital altitudes of SEDSAT. Moreover, SEDSAT is not a 3-axis-stabilized satellite and, consequently, its frontal area with respect to the wind velocity changes continually. A rough estimate of the lifetime can be obtained from relatively simple formulas obtained under simplifying assumptions as follows: spherical and corotating atmosphere, exponential atmospheric density, and average frontal area of satellite.

In accordance with the previous assumption analytical formulas can be obtained for the decay of the orbit semi-major axis per revolution Δa_{rev} [4]. The orbital decay from an elliptical orbit due to atmospheric drag can be subdivided into two phases: (a) a circularization phase during which the apogee decays while the perigee altitude remains the same; and (b) a spiraling phase from a circular orbit to final reentry.

From the conservation of angular momentum, the velocity along the orbit can be readily obtained as follows:

$$v^2 = \left(\frac{\mu}{Q}\right)^2 (1 + e \cos\theta)^2 \approx \left(\frac{\mu}{Q}\right)^2 (1 + 2e \cos\theta) \quad (9.1)$$

where Q is the angular momentum for unit mass and the approximation on the right hand side is valid for eccentricity $e \ll 1$.

If an atmosphere corotating at the Earth angular speed Ω_E is considered, then

$$v^2 \approx \left(\frac{\mu}{Q}\right)^2 (1 + 2e \cos\theta) \left(1 - 2 \frac{\Omega_E}{\Omega} \cos i (1 - e \cos\theta)\right) \quad (9.2)$$

where i is the orbital inclination and Ω the instantaneous orbital rate.

By utilizing eqn. (9), the drag force on the system can be written as:

$$F = \frac{1}{2} C_D A \rho_0 \exp(h_0/H) \exp(-h/H) v^2 \quad (10)$$

An exponential atmospheric density profile has been assumed in eqn. (10) with reference density and reference height ρ_0 and h_0 , and scale height H .

From the orbital energy loss per unit mass due to atmospheric drag

$$\frac{da}{dt} = \frac{2F}{\Omega m} \quad (11)$$

the semi-major axis decay per revolution is readily obtained as follows:

$$\Delta a_{rev} = \int_0^P \frac{2F}{\Omega m} dt \quad (12)$$

where P is the orbital period. It is more convenient to integrate eqn. (12) with respect to the orbital anomaly $d\theta$. Since,

$$dt = \frac{1}{\Omega_0(1 + 2e \cos \theta)} d\theta \quad (13)$$

with Ω_0 the mean orbital rate, eqn. (12) yields

$$\Delta a_{rev} = \frac{C_D A}{m} K a^2 \int_0^{2\pi} e^{\psi \cos \theta} (1 + 2e \cos \theta) d\theta \quad (14)$$

where

$$K = \rho_0 \exp[(h_0 + R_E - a)/H] (1 - 2\Omega_E \sin i / \sqrt{\mu/a^3}) \quad (15.1)$$

$$\psi = ea/H \quad (15.2)$$

R_E is the Earth's equatorial radius and a the semi-major axis of the orbit.

The integral in eqn. (14) can be decomposed into two elliptical integrals giving rise to two *modified Bessel functions* of order zero and one, respectively. In conclusion, after some algebraic manipulations:

$$\Delta a_{rev} = -2\pi(C_D A / m) a^2 K [I_0(\psi) + 2eI_1(\psi)] \quad \text{for } e \ll 1 \quad (16.1)$$

$$\Delta a_{rev} = -2\pi(C_D A / m) a^2 K \quad \text{for } e \approx 0 \quad (16.2)$$

Equation (16.2) applies to the spiraling phase in which $e \approx 0$ and, consequently, $I_0(0) = 1$ and $I_I(0) = 0$.

In eqns. (16), $C_D A/m = 1/\beta$ where β is the satellite ballistic coefficient. Different values of h_0 should be adopted in eqns. (16.1) and (16.2) for the circularization and spiraling phases in order to provide good local fits of the density in the two regions of interest ($h_0 = h_p$, with h_p the perigee height, does not necessarily produce the best results for orbits with small eccentricities). If $h_0 = h_p$ and $\Omega_E = 0$ (i.e., without the rotating atmosphere), then $K = \rho_p \exp(-\psi)$ and eqns. (9) reduce to more familiar formulas [5].

The decay time can be computed as follows [4]:

$$\Delta t = \int_{a_f}^{a_i} \frac{\pi}{\Delta a_{rev} \sqrt{\mu/a^3}} da \quad (17)$$

where a_i and a_f are the semi-major axis associated with the initial and final altitudes of the two decay phases under consideration. The integral of eqn. (17) must be computed twice for the two expressions of Δa_{rev} of eqns. (16.1) and (16.2) and, moreover, a_f (circularization phase) = a_i (spiraling phase) = a_p (semi-major axis at perigee of circularization phase). The orbital lifetime is the sum of the decay times of the circularization and spiraling phases.

Figure 2 shows the total lifetime for the SEDSAT satellite, computed from eqns. (16) and (17), with the following numerical values: $\beta = 118$, $a_p = 330$ km, and $T_{exo} = 750$ K. This value of the exospheric temperature is the current best estimate for a SEDSAT launch date in July 1997.

The lifetime estimate, shown in Fig. 2, was compared to the lifetime estimated at NASA Marshall Space Flight Center (NASA/MSFC) by means of a computer code with a more accurate atmospheric model in which the lifetime is also a function of the argument of perigee. The lifetime of Fig. 2 is an average value of the more general values estimated at NASA/MSFC. It is evident from Fig. 2 that in order to have a lifetime ≥ 3 years, the initial altitude of apogee must be ≥ 530 km (with respect to a spherical Earth). Both estimates of lifetime (SAO and MSFC), however, are affected by the large uncertainties associated with the prediction of the actual Solar activity and, hence, atmospheric conditions a few years in advance.

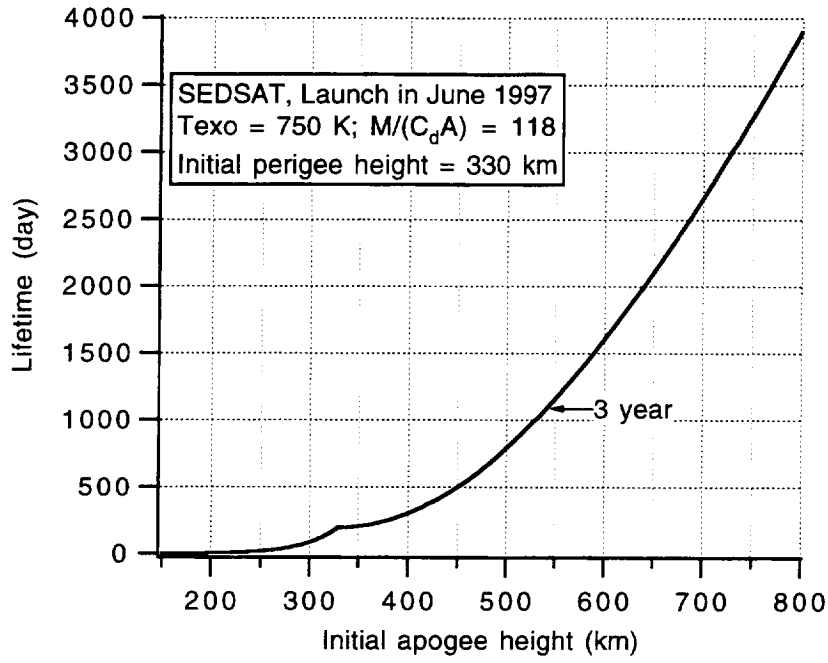


Fig. 2. SEDSAT lifetime vs apogee height.

1.4 Control of SEDSAT Deployment

SEDS Deployer's Tension Model

Before attacking the problem of controlling SEDSAT deployment and release, a few words must be said about the deployer's tension model. The reader should consult Ref. [6] for a more detailed treatment of the subject. The tension model for the SEDS deployer is as follows:

$$T = \left[T_0 + I \rho \dot{L}^2 A_{rel}^{-E} \right] \cdot e^B \cdot e^{f \cdot |\theta_0 - \theta|} \quad (18)$$

where $A_{rel} = 1 - A L/L_{end}$, L_{end} = final tether length = 20 km, A = tether annulus solidity = 0.942, E = area exponent = 0.6, B = brake parameter = $2\pi f n$, n = number of brake turns, f = friction coefficient = 0.18 (best estimate), T_0 = static (or minimum) tension, I = inertia multiplier = 4.1, ρ = linear density of tether = 3.3 kg/km, θ_0 = null exit angle, and θ = tether's exit angle (for a deployer aligned along the Nadir, θ coincides with the in-plane libration angle). In summary, this approximate tension model consists of a static tension term T_0 , an hydraulic tension term proportional to \dot{L}^2 , an exponential brake multiplier, and an exponential exit-angle multiplier. Parameters of the tension model are uncertain as they depend on environmental conditions and many other uncontrollable, or

poorly controllable, factors. The most influential, from the deployment dynamics standpoint, and also less certain parameter of the tension model is T_0 . A likely estimate of the value of T_0 from the flights of SEDS-I and II is about 20 mN with an expected variability of ± 10 mN.

SEDS-II-Type Deployment Control Law Attempts

A non-linear control law that made use of the feedback linearization technique was successfully tested during the flight of SEDS-II in March 1994. This control law utilized predetermined tether length, tether rate, and brake reference profiles in order to eliminate the non-linearities in the model of the plant (deployer) and the actuator (brake). A locally linear feedback, based on error signals of the actual length and rate with respect to the reference values, was used to correct the reference brake profile in order to track the reference trajectory in the state space under off-reference conditions. This control law was active throughout the SEDS-II deployment with the only exception of the first kilometer of deployed tether. The reference profiles for SEDS-II were designed to provide a null libration at the end of deployment. If the same technique were applied to SEDSAT, the reference profiles should be designed to provide a large libration at the end of deployment or equivalently a large angular rate at the crossing of LV.

The first attempts for controlling SEDSAT deployment were carried out by simply utilizing the same technique adopted successfully for deploying SEDS-II. The ejection velocity was 1.47 m/s (i.e., the ejection velocity of SEDS-II scaled by $\sqrt{m_1/m_2}$ where $m_1 = 34$ kg and $m_2 = 26$ kg are the masses of SEDSAT and SEDS-II, respectively). The final state vector was specified as to obtain the desired horizontal velocity at the crossing of the local vertical (LV) with a tether length of 20 km. The horizontal velocity of the released-system CM $\Delta V_{CM,H}$ at LV crossing (with respect to an LH-LV rotating reference frame) is simply the swinging component of the ΔV as follows

$$\Delta V_{CM,H} = \Delta V_{swing} = \sqrt{3}\Omega \sin(\bar{\theta}) L_{CM} \quad (19)$$

and, consequently, it depends upon the maximum libration amplitude at the fully deployed tether length.

In the following, we describe some sample reference profiles and the associated feedback control that were derived in order to attempt a control of SEDSAT deployment along the same line of the SEDS-II deployment.

In SEDSAT_Ref12 (the numbering is sequential from the beginning of the SEDSAT control law analysis), the final state vector is as follows:

$$L = 20 \text{ km}, \dot{L} = 0.1 \text{ m/s}, \theta = 0, \dot{\theta} = 0.077 \text{ deg/s (i.e., } \Delta V_{CM,H} = 24 \text{ m/s)}.$$

The initial conditions at satellite ejection are $V_0 = 1.47 \text{ m/s}$ and $\theta_0 = 0^\circ$ (ejection along LV upwards). The value quoted above for the horizontal component $\Delta V_{CM,H}$ corresponds to a final libration amplitude of 42° . The brake is activated at $t = 750 \text{ s}$ (i.e., $L = 1060 \text{ m}$) and the reference value of the minimum tension is 20 mN . The position and velocity gains of the feedback portion of the control law are $K_1 = 0.004$ and $K_2 = 0.4$, respectively. These values of the gains are larger than those adopted in SEDS-II in order to make the control law more effective in tracking the tether length and velocity profiles. Figure 3(a) shows the deployment dynamics for the reference value $T_0 = 20 \text{ mN}$ while Figs. 3(b)-3(f) show the dynamics for values of T_0 ranging from 10 mN to 30 mN . It is clear that the control law is sufficiently insensitive to variations of the minimum tension but, because of the insufficient final libration amplitude, it is unable to provide the required ΔV at LV crossing.

In reference profile SEDSAT_Ref19, the final state vector is as follows:

$$L = 20 \text{ km}, \dot{L} = 0.1 \text{ m/s}, \theta = 0, \dot{\theta} = 0.09 \text{ deg/s (i.e., } \Delta V_{CM,H} = 27 \text{ m/s)}.$$

The ejection angle this time is $\theta_0 = -20^\circ$ (upward and forward).

The value quoted above for the horizontal component $\Delta V_{CM,H}$ corresponds to a final libration amplitude of about 47° . The brake is activated at $t = 500 \text{ s}$ ($L = 700 \text{ m}$) and the reference value of the minimum tension is 20 mN . Figures 4(a)-4(f) show that the final ΔV at LV crossing (or equivalently the final libration amplitude) is not large enough to provide the desired apogee altitude after satellite release. In fact, with a 297-km circular orbit for the Shuttle and a tether length of 20 km , a final libration amplitude $\geq 60^\circ$ is required for attaining an apogee altitude $\geq 530 \text{ km}$. Moreover, the insensitivity of the ΔV magnitude at LV crossing with respect to variations of the tension model parameters is not satisfactory.

In reference profile SEDSAT_Ref24, the final state vector is as follows:

$$L = 20 \text{ km}, \dot{L} = 0.1 \text{ m/s}, \theta = 0, \dot{\theta} = 0.096 \text{ deg/s (i.e., } \Delta V_{CM,H} = 31 \text{ m/s)}.$$

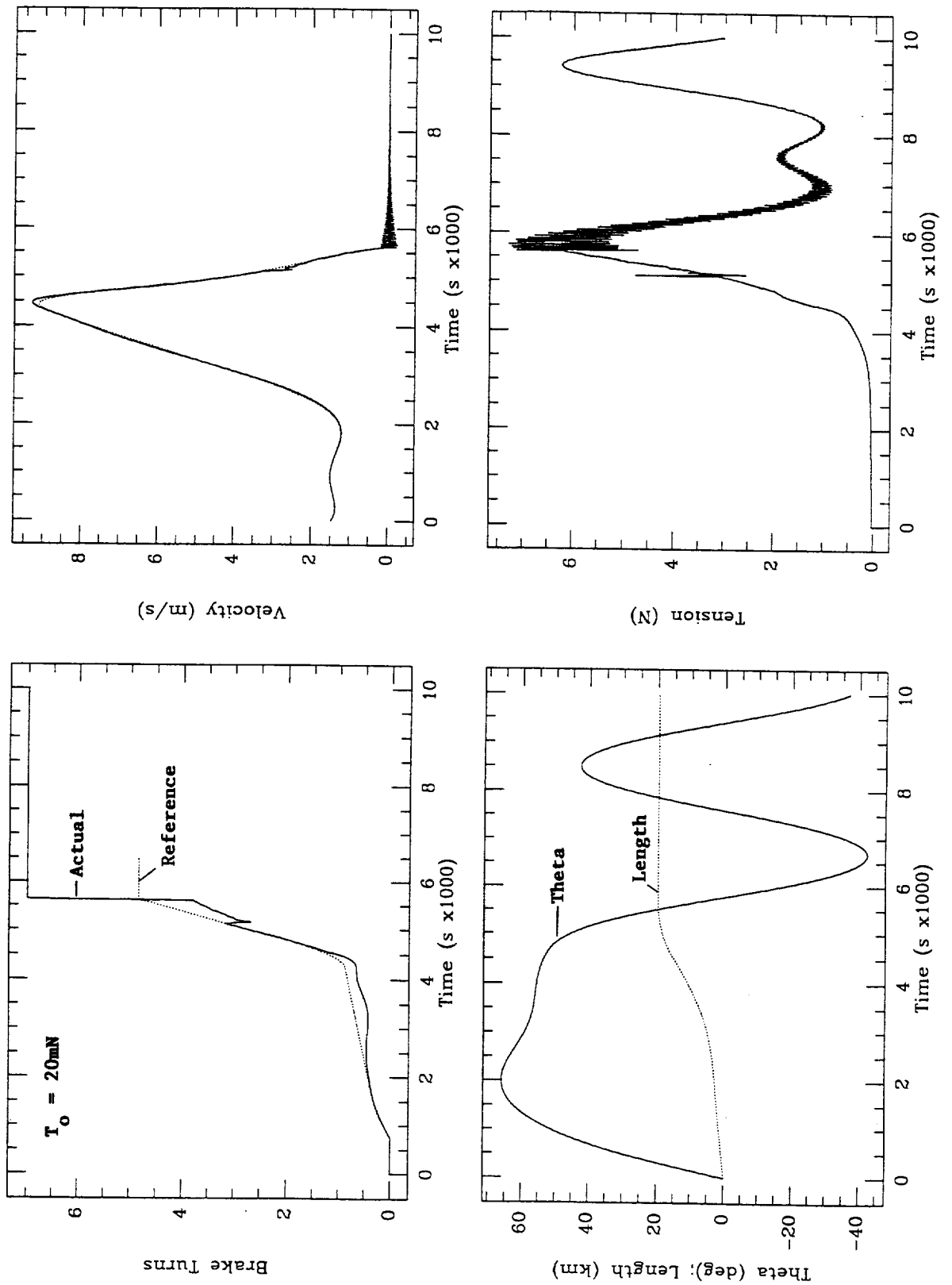


Fig. 3(a). Deployment dynamics for SEDS-II-type reference profile 12 (see text).

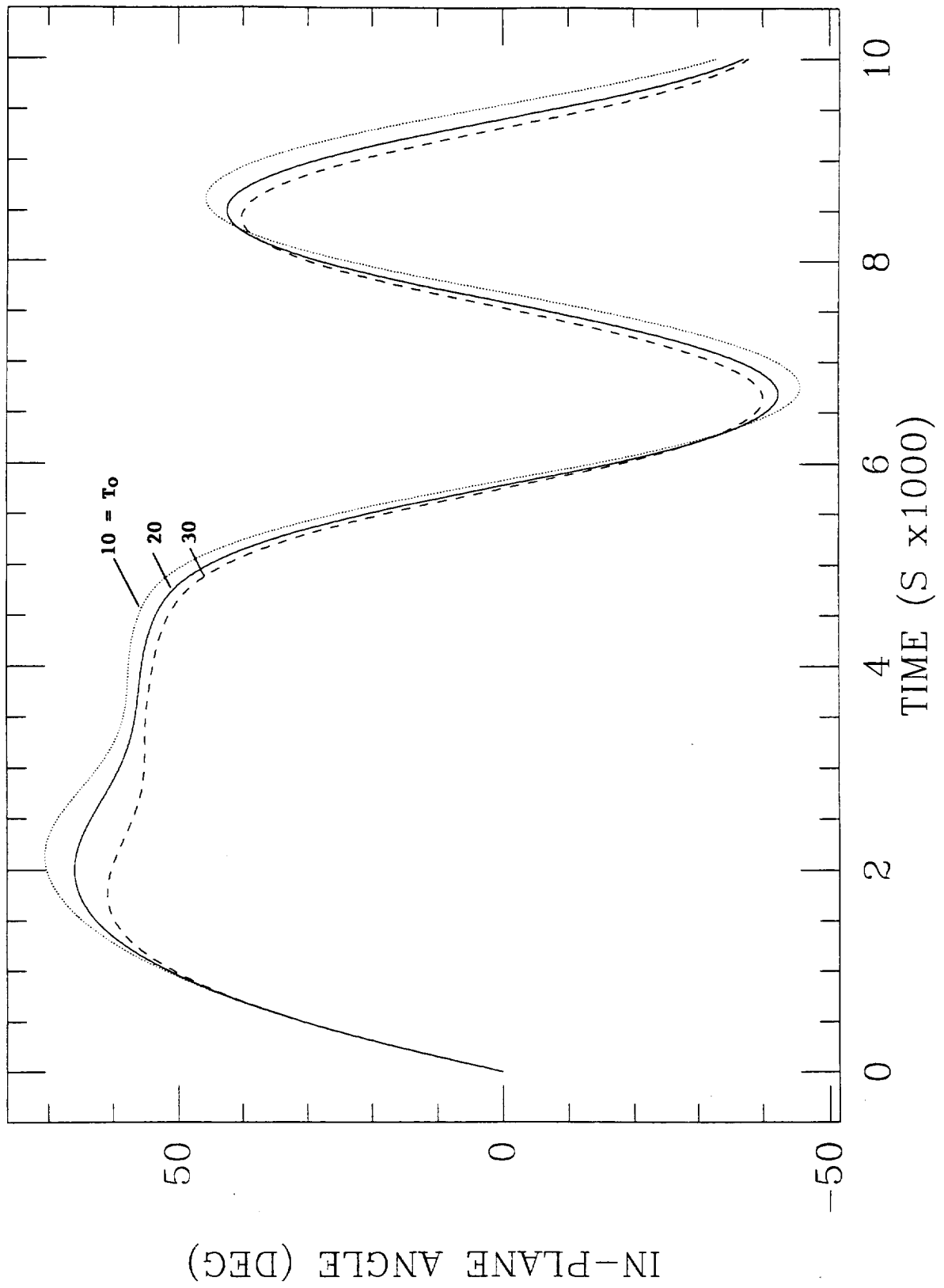


Fig. 3(b). Deployment dynamics for SEDS-II-type reference profile 12 (see text).

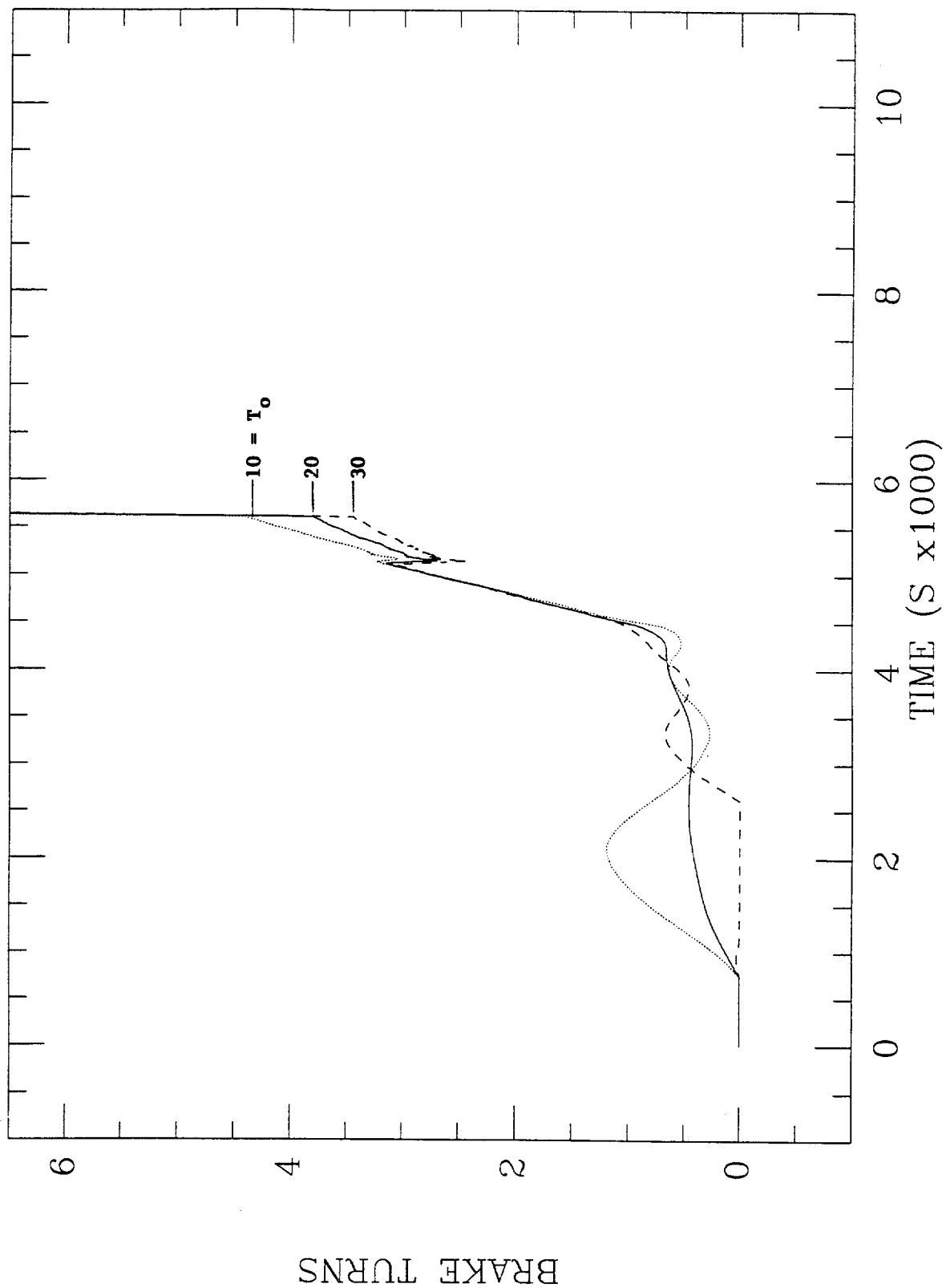


Fig. 3(c). Deployment dynamics for SEDS-II-type reference profile 12 (see text).

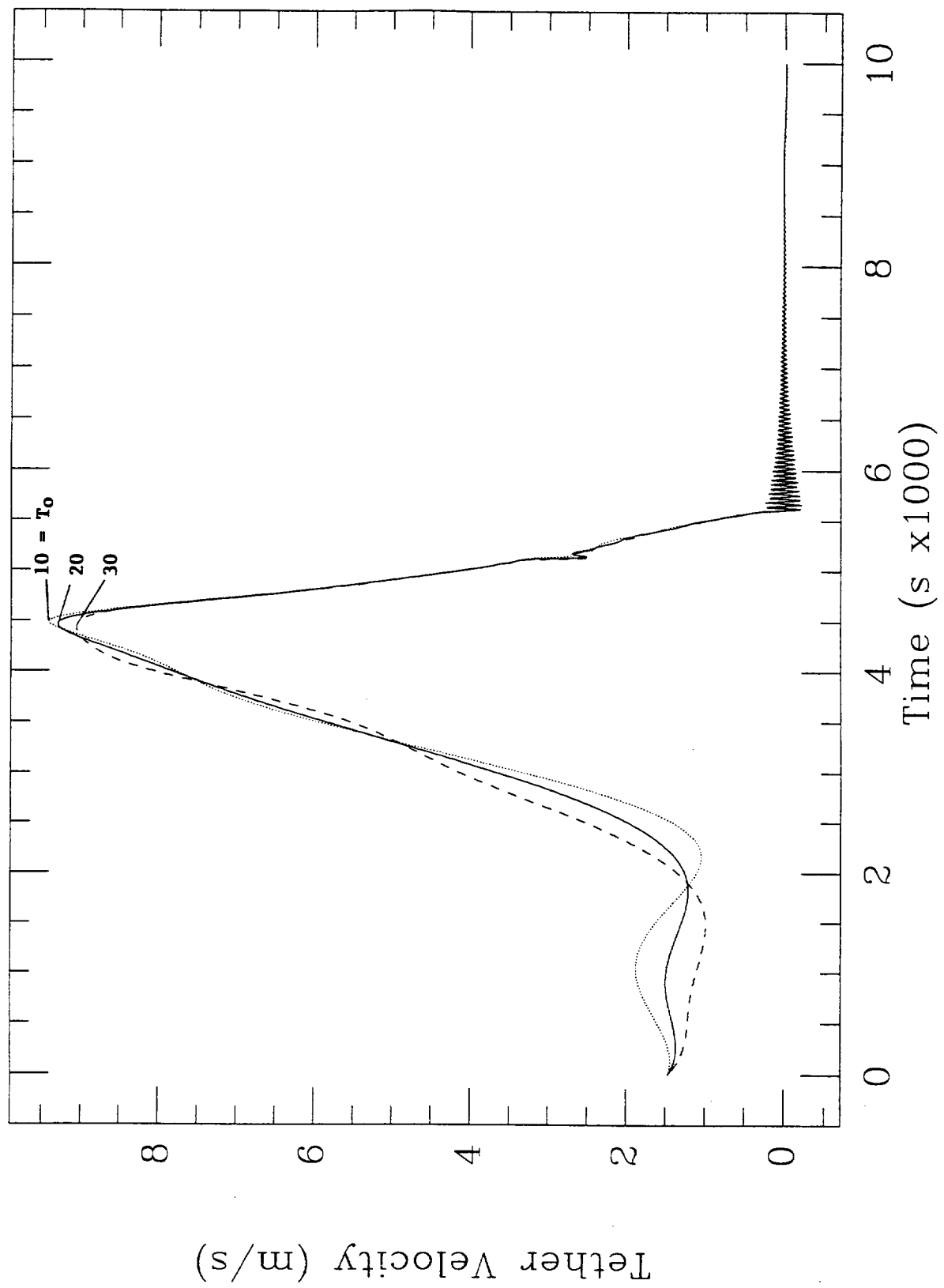


Fig. 3(d). Deployment dynamics for SEDS-II-type reference profile 12 (see text).

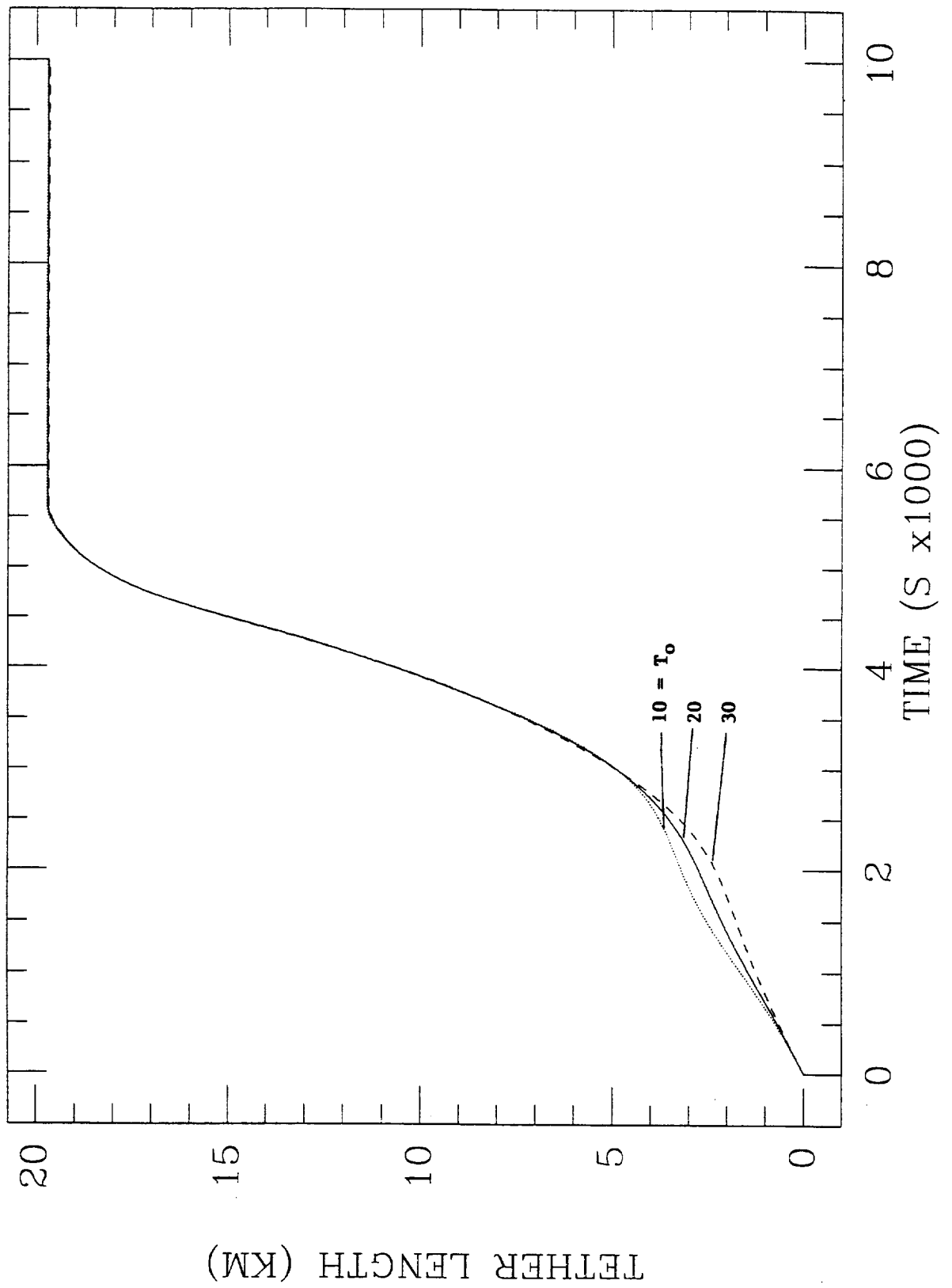


Fig. 3(e). Deployment dynamics for SEDS-II-type reference profile 12 (see text).

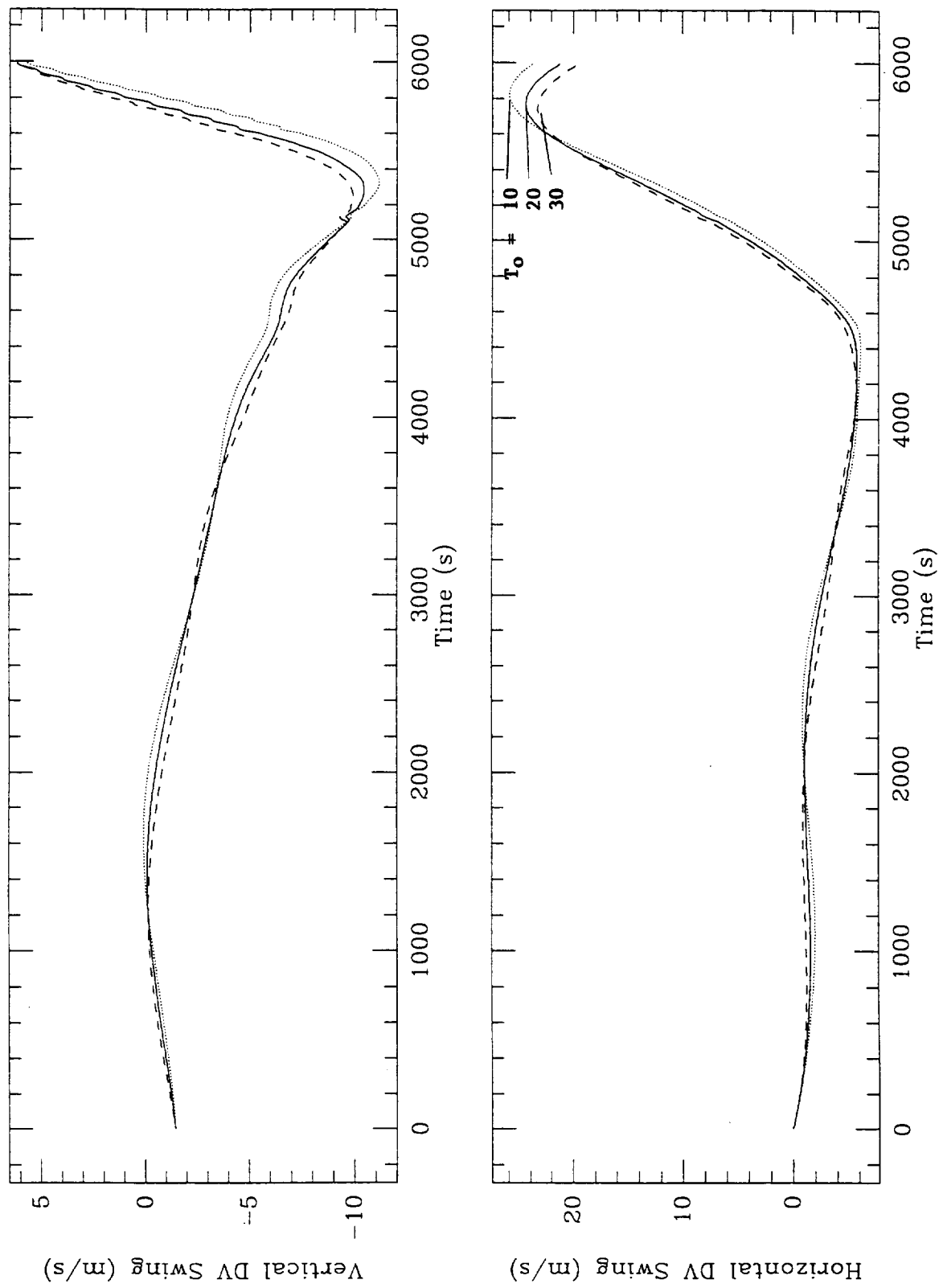


Fig. 3(f). Deployment dynamics for SEDS-II-type reference profile 12 (see text).

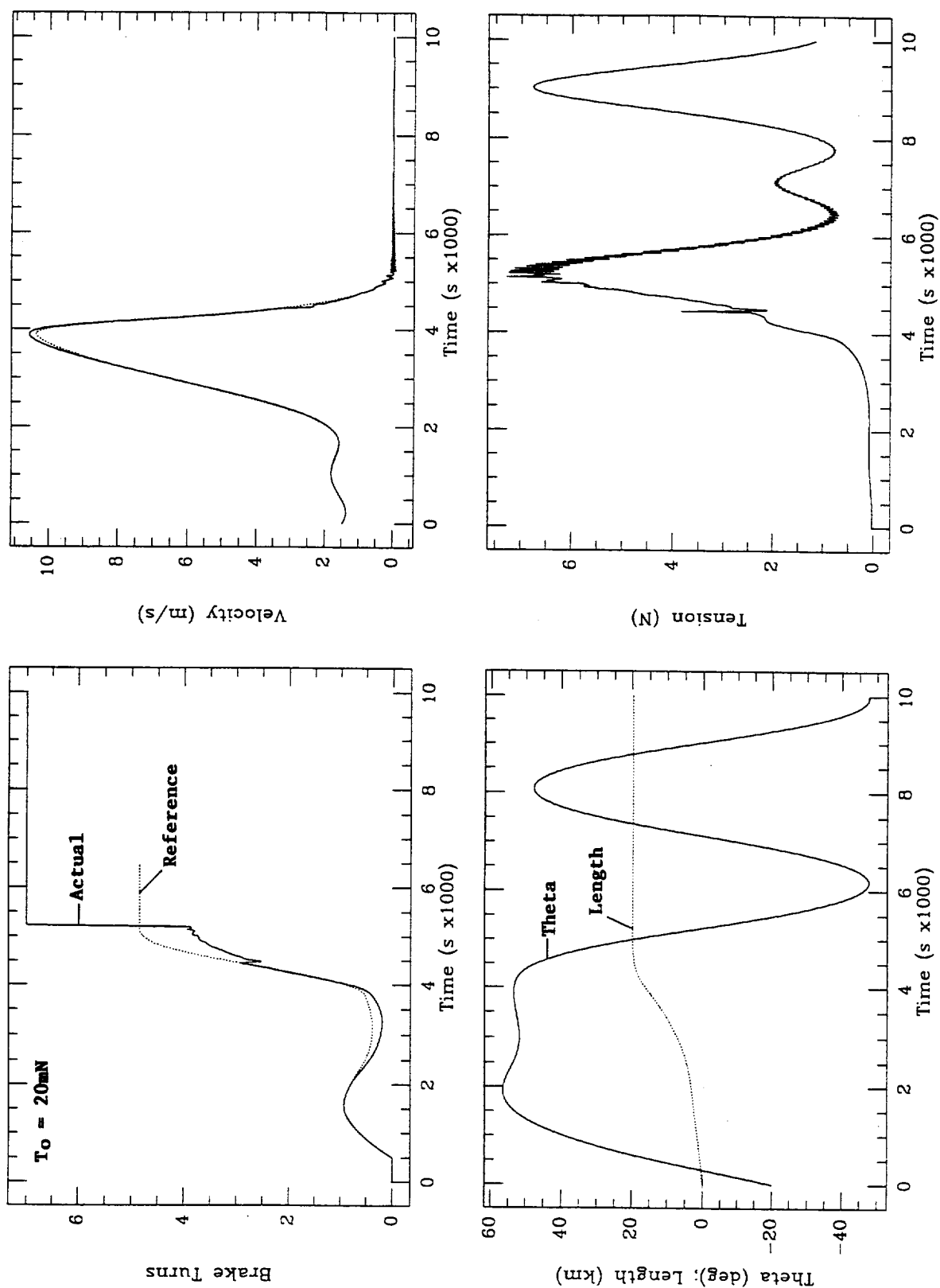


Fig. 4(a). Deployment dynamics for SEDS-II-type reference profile 19 (see text).

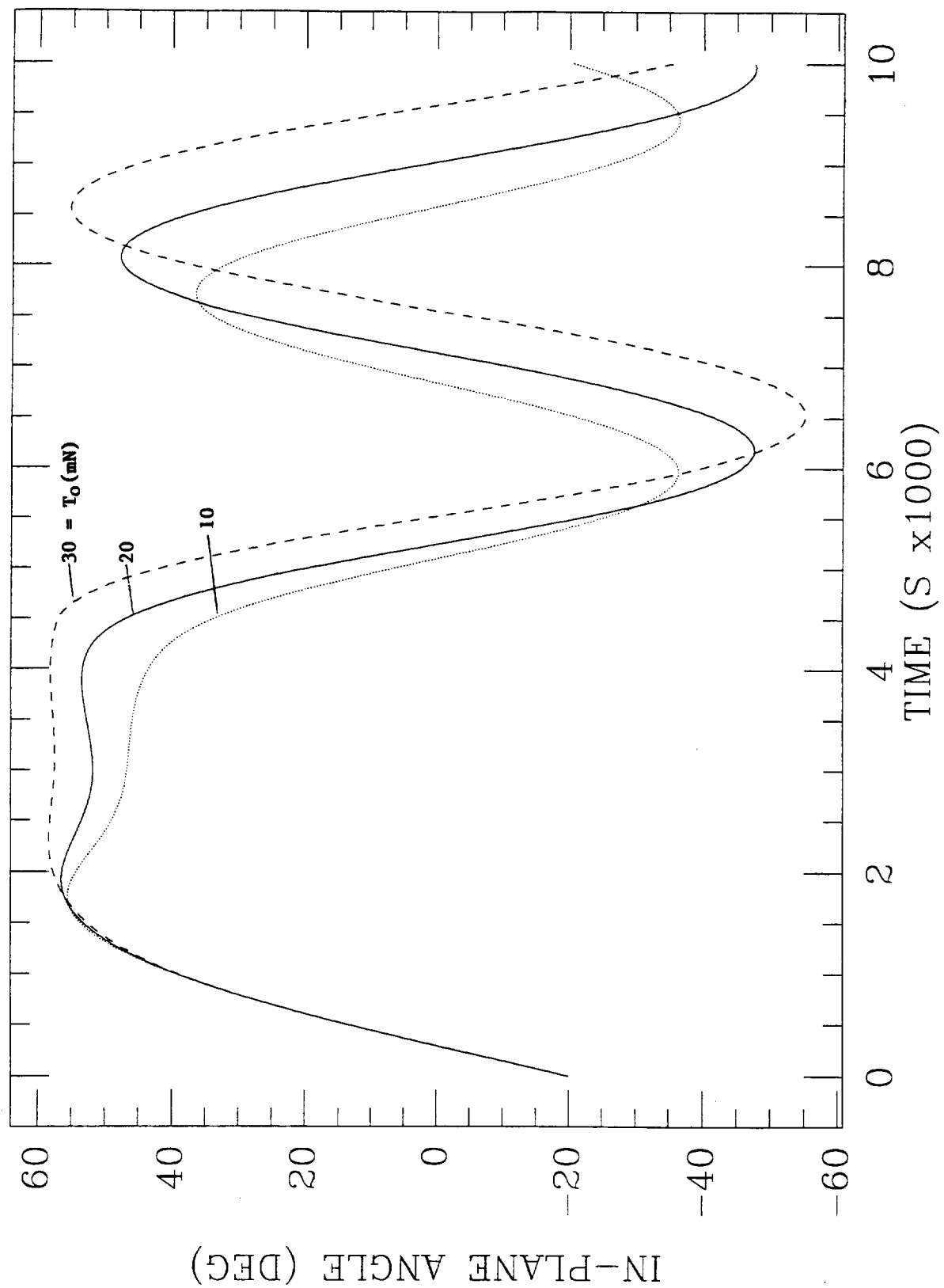


Fig. 4(b). Deployment dynamics for SEDS-II-type reference profile 19 (see text).

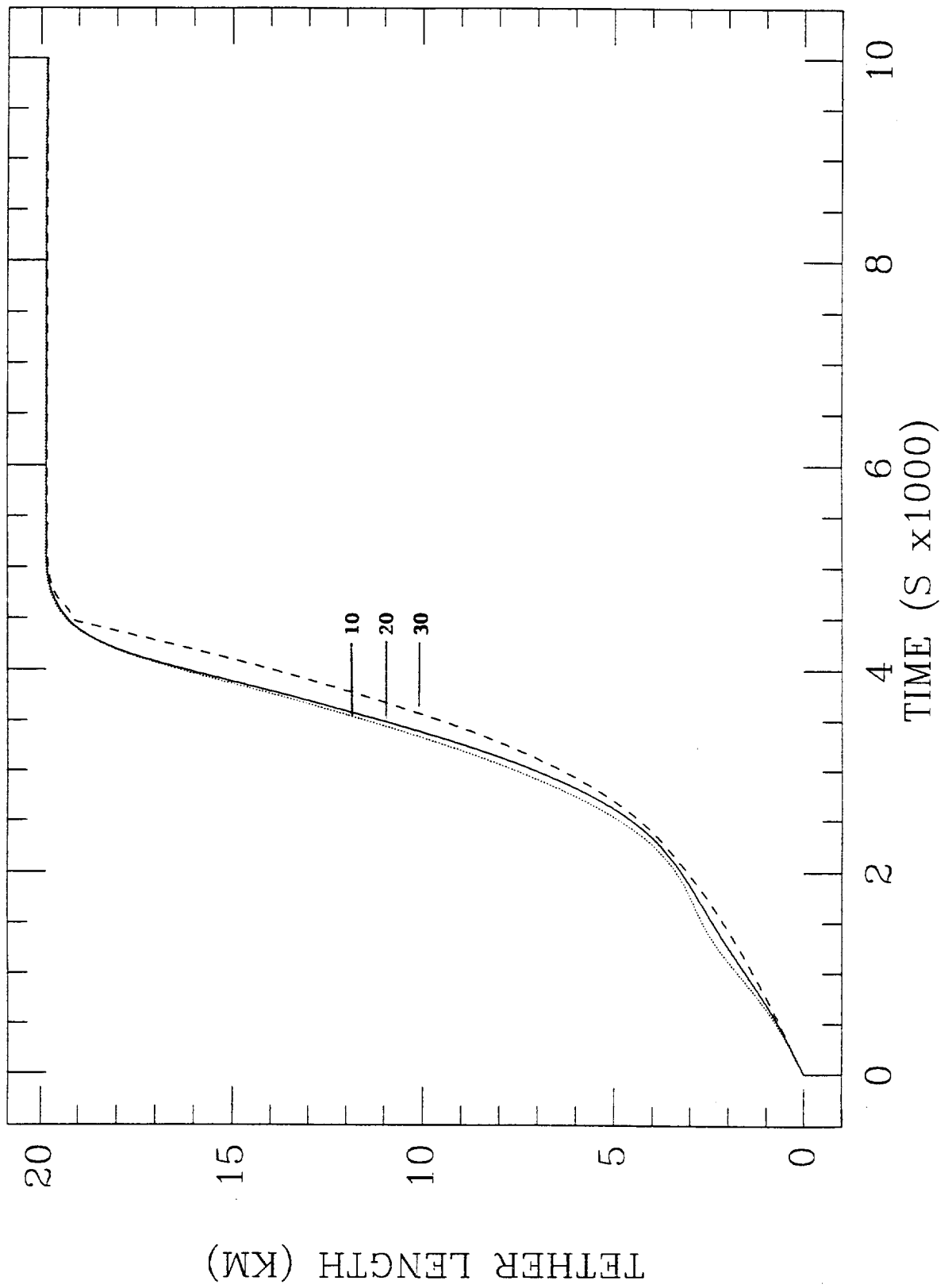


Fig. 4(c). Deployment dynamics for SEDS-II-type reference profile 19 (see text).

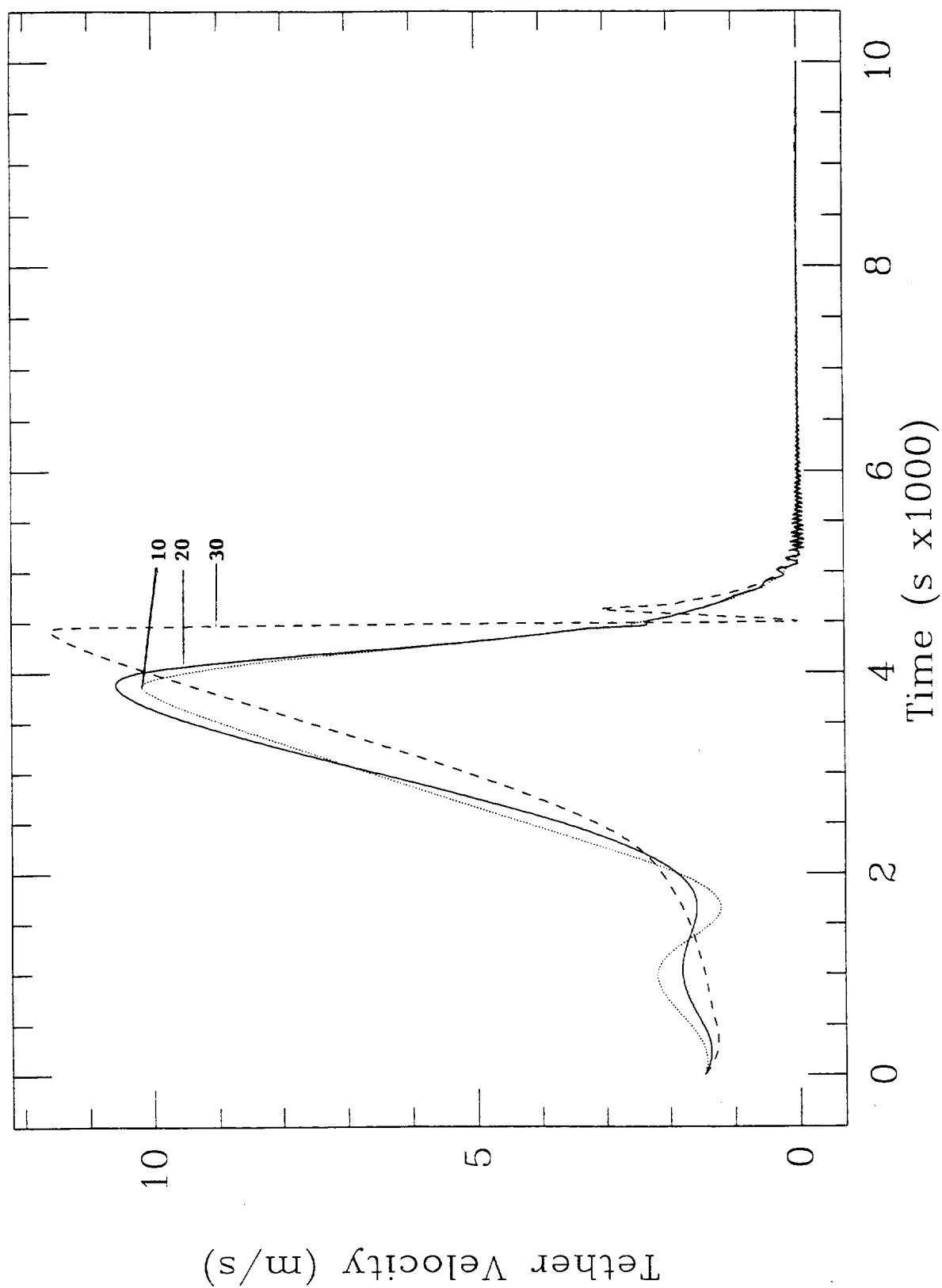


Fig. 4(d). Deployment dynamics for SEDS-II-type reference profile 19 (see text).

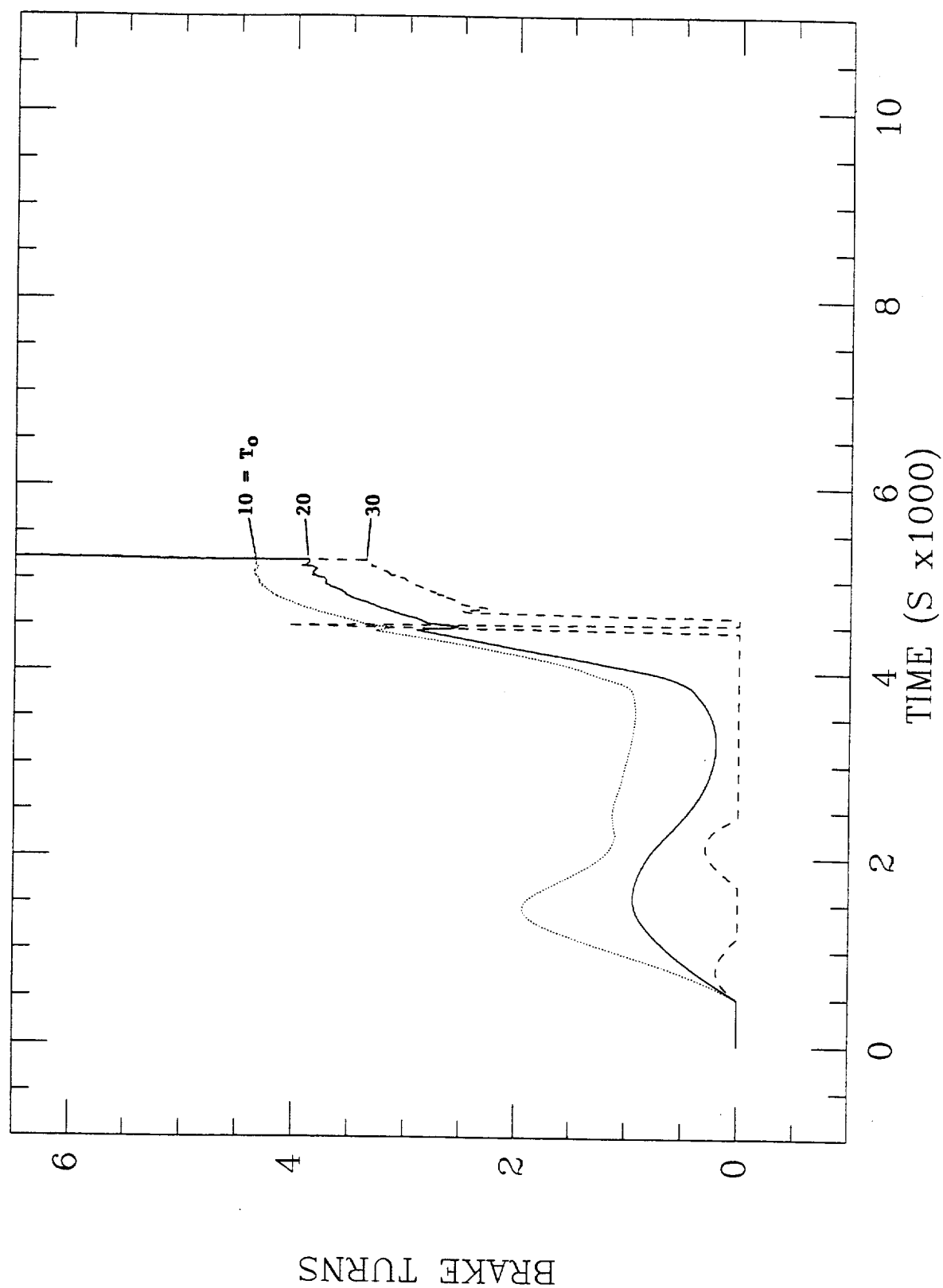


Fig. 4(e). Deployment dynamics for SEDS-II-type reference profile 19 (see text).

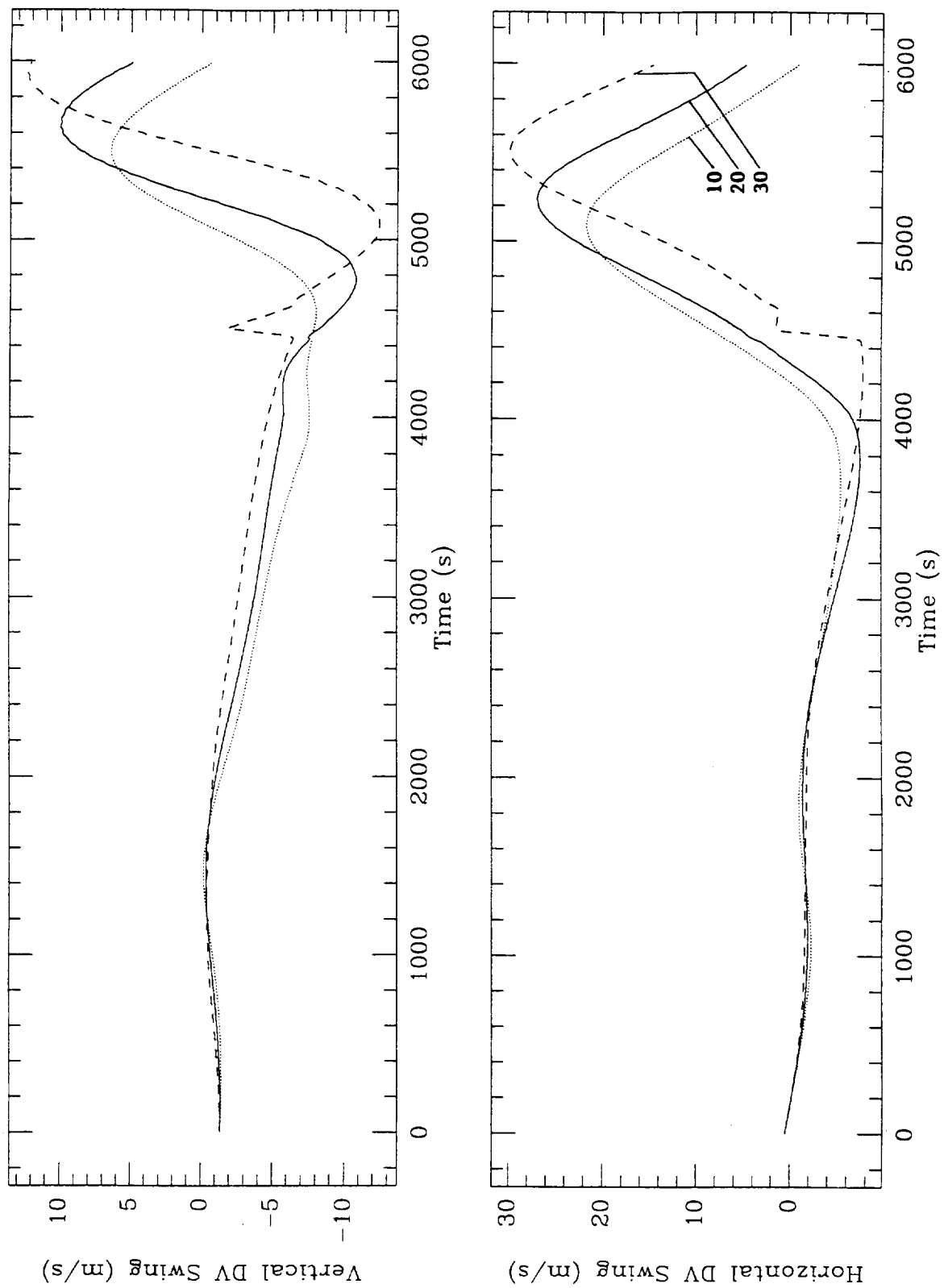


Fig. 4(f). Deployment dynamics for SEDS-II-type reference profile 19 (see text).

The ejection angle is $\theta_0 = -20^\circ$, the brake is activated at $t = 3840$ s ($L \approx 16$ km) and the reference value of the minimum tension is 20 mN. The value quoted above for $\Delta V_{CM,H}$ corresponds to a final libration amplitude of about 57° . The deployment dynamics for this case (see Figs. 5(a)-5(f)) shows that the ΔV and the timing at LV crossing are sensitive to variations of the model parameters. The magnitude of the ΔV at LV crossing, however is close to the value required for reaching the desired apogee height.

At this point we must address briefly the stability of the deployment maneuver as SEDS-II and SEDSAT operate in different regions of the phase-space $\theta - \dot{\theta}$: in SEDS-II the in-plane angle was $< 45^\circ$ for most of deployment while in SEDSAT, because of the required ΔV , it must be $> 60^\circ$ for most of the deployment.

The equation of in-plane libration of a two-mass tethered system with respect to an LH-(ascending) LV reference frame, reported here below,

$$\ddot{\vartheta} + 2\frac{\dot{L}}{L}(\dot{\vartheta} + \Omega) + \frac{3}{2}\Omega^2 \sin(2\vartheta) = 0 \quad (20)$$

becomes autonomous for $\dot{L}/L = \text{constant}$, i.e., for exponential (as function of time) maneuvers. Consequently, the stability of solutions can be analyzed in the time-invariant state space $\theta - \dot{\theta}$. Trajectories in the state space with $\theta > 45^\circ$ or $\theta < -45^\circ$ are unstable as they fall into the spheres of influence of two saddle points in the state space [7-8]. Figure 6 shows the phase-space diagram for an exponential deployment (i.e., $L = \alpha \dot{L}$ with α the rate parameter and to every α corresponds an in-plane angle $\bar{\theta}$ with respect to LV which is constant throughout the exponential deployment) with $\bar{\theta} = 15^\circ$. When the rate parameter and, consequently, $\bar{\theta}$ are increased to 45° , the two saddle points of Fig. 6 move to the $+45^\circ$ and -45° points, respectively. In this situation, the stability margin is lost because the deployment trajectories are necessarily around the saddle points. The analysis in Refs. [7-8] applies, strictly speaking, to exponential maneuvers. Reference profiles for the SEDS-II-type control law are for a large portion exponential. The stability analysis above, therefore, provides indications about the stability of close-to-exponential reference profiles to be confirmed with dynamics simulations.

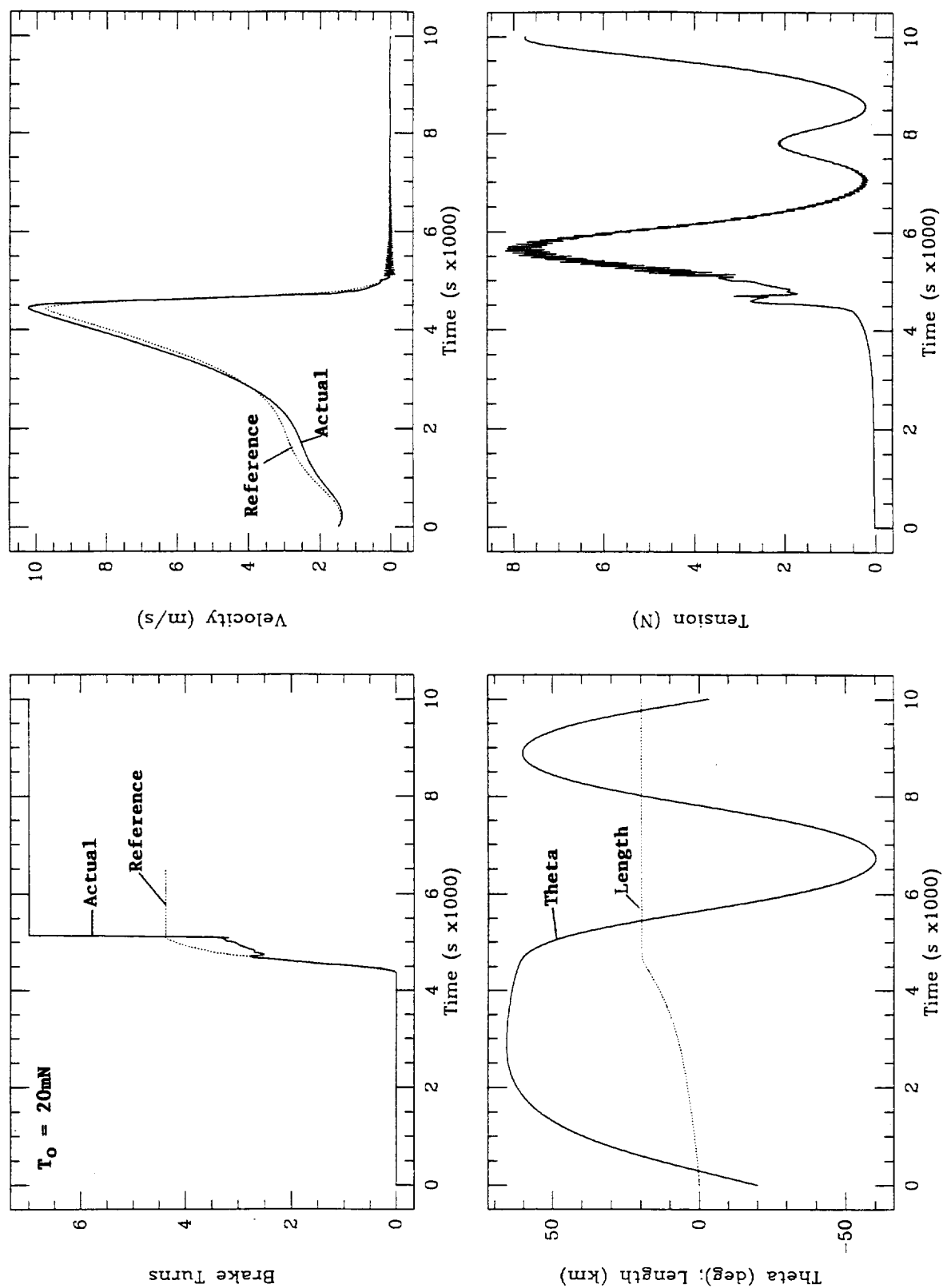


Fig. 5(a). Deployment dynamics for SEDS-II-type reference profile 24 (see text).

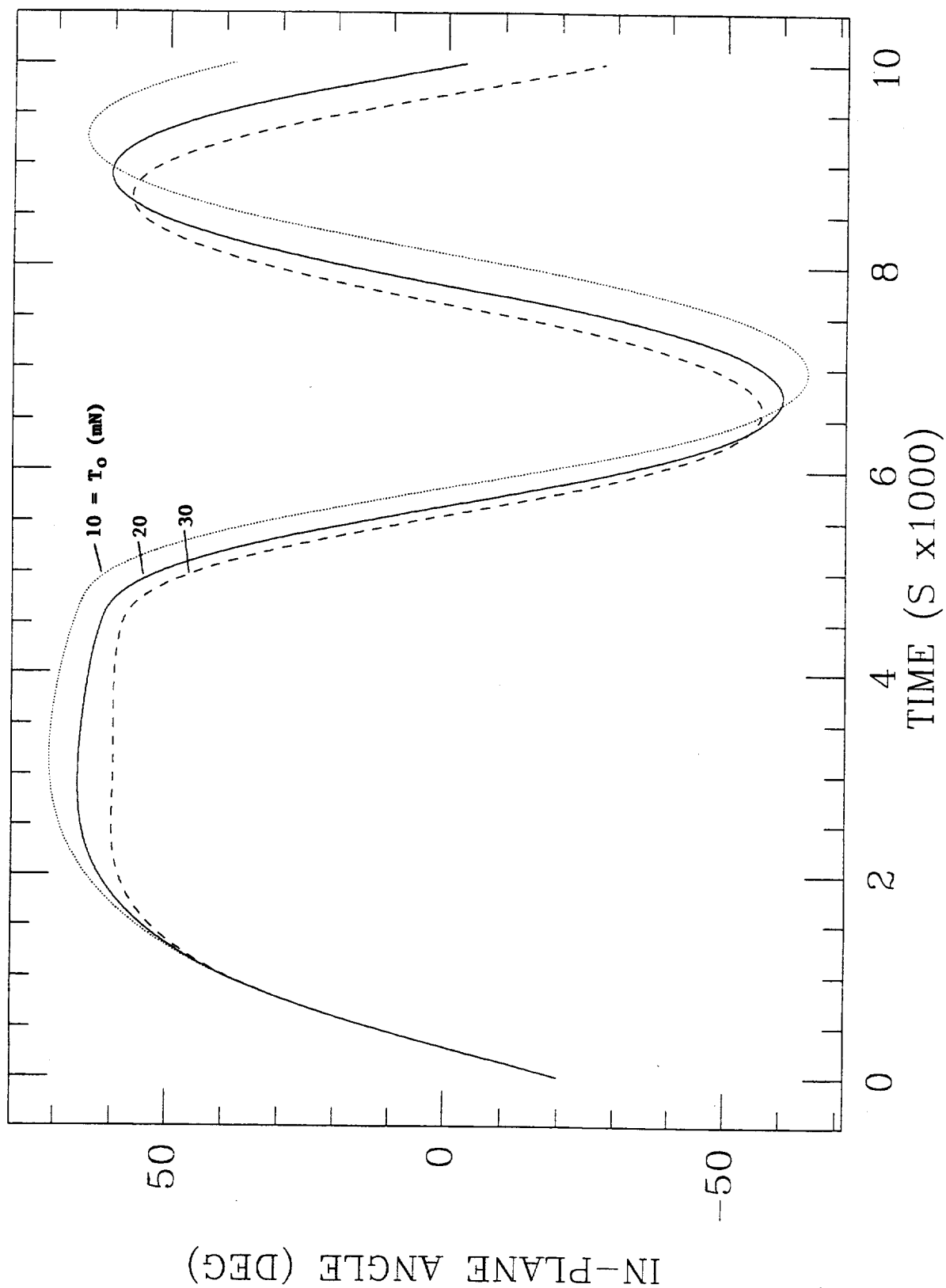


Fig. 5(b). Deployment dynamics for SEDS-II-type reference profile 24 (see text).

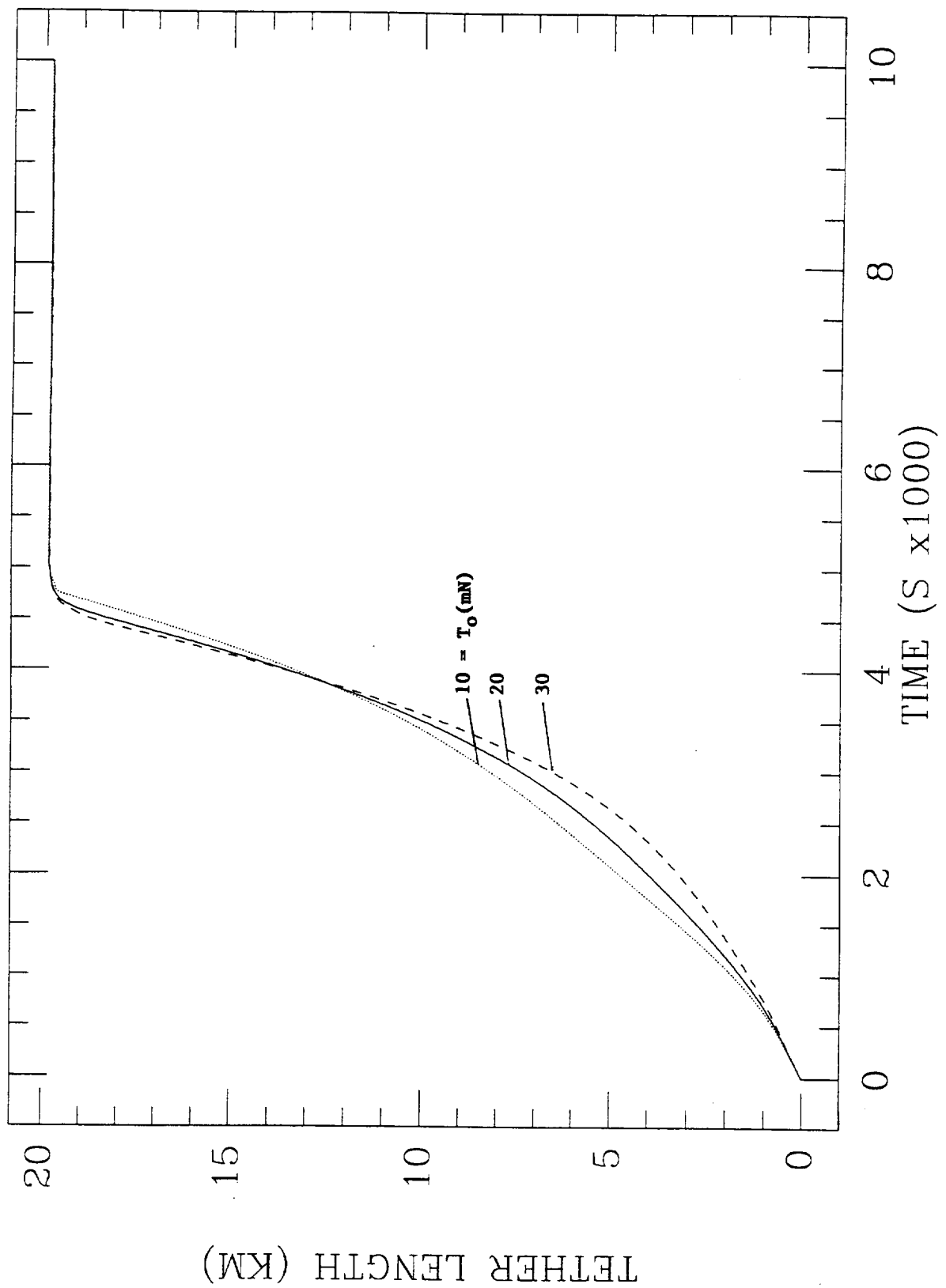


Fig. 5(c). Deployment dynamics for SEDS-II-type reference profile 24 (see text).

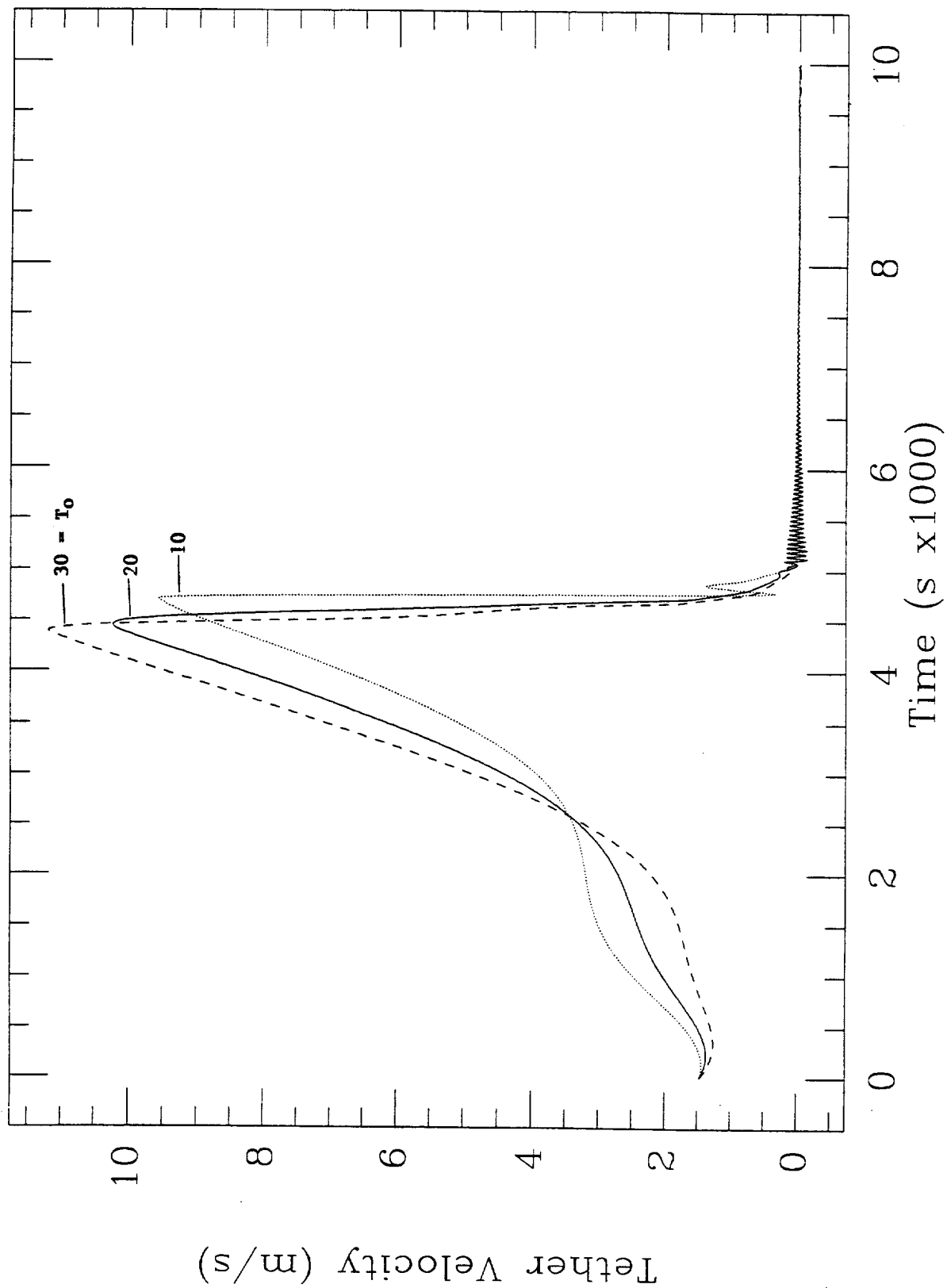


Fig. 5(d). Deployment dynamics for SEDS-II-type reference profile 24 (see text).

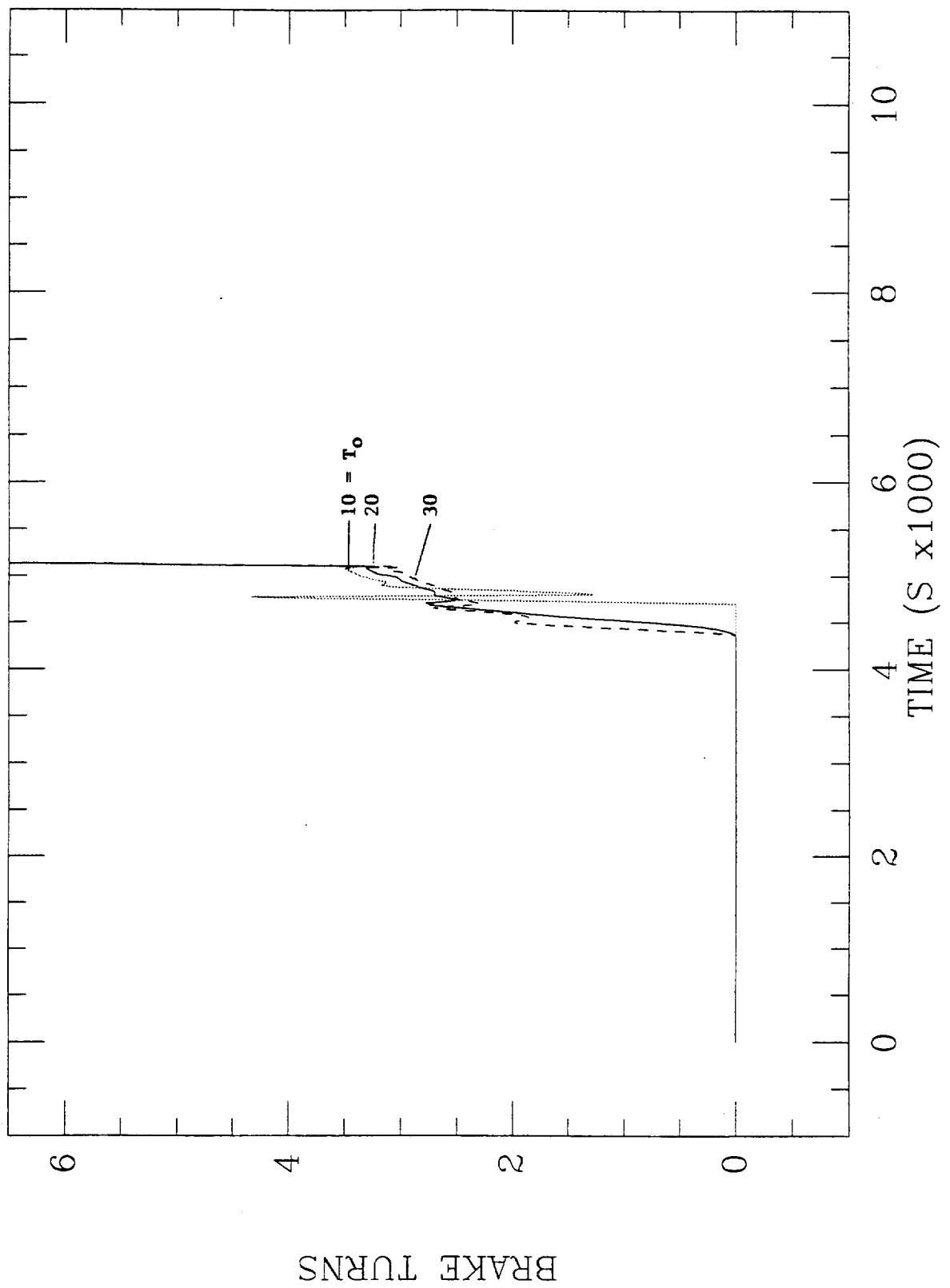


Fig. 5(e). Deployment dynamics for SEDS-II-type reference profile 24 (see text).

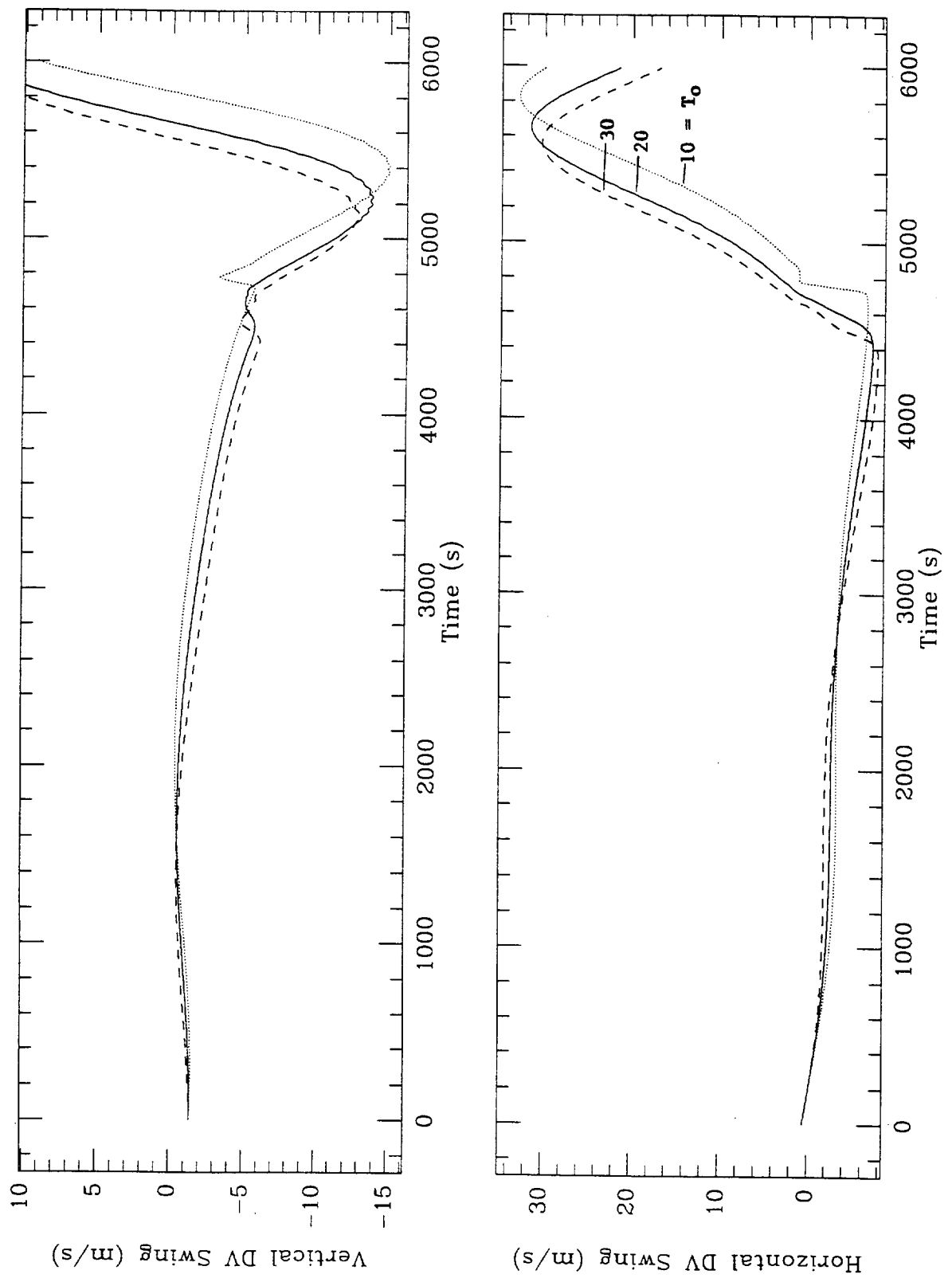
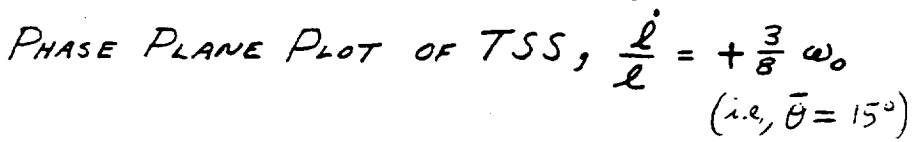


Fig. 5(f). Deployment dynamics for SEDS-II-type reference profile 24 (see text).



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New Deployment Control Law

All attempts at controlling SEDSAT with the strategy adopted for SEDS-II resulted in an unstable response of the in-plane angle and, consequently, in an unsatisfactory robustness of the control law with respect to variations of the deployer model's parameters. Satisfactory results, as shown earlier, could be obtained only for final libration angles $< 45^\circ$ (which are too small for providing the required ΔV at release) confirming the conclusions of the time-invariant stability analysis of Refs. [7-8].

A different control strategy was followed for SEDSAT aimed at obtaining a high ΔV (and hence a high final libration angle) and, at the same time, satisfactory insensitivity to variations of the model parameters.

The sensitivity of the ΔV at release vs the initial conditions at satellite ejection for different values of the deployer model's parameters was analyzed numerically by using two different simulators for tethered systems dynamics [8-10]. The analysis of the sensitivity of the final libration angle (which is related to ΔV_H) to the initial conditions at satellite ejection from the Shuttle was carried out by J. Pelaez, visiting the Smithsonian Astrophysical Observatory from the Politechnical University of Madrid. The results are plotted in Fig. 7 vs the non-dimensional tension parameter

$$\Lambda = \frac{m L_{\text{End}} \Omega^2}{T_0} \quad (21)$$

It is interesting to notice that for values of the ejection velocity $V_0 > 3.88$ m/s, there are suitable values of the ejection angle for which the desired final libration amplitude is independent of variations of the minimum tension. However, these value of the ejection velocity are too high for Shuttle deployment operations in which the possibility of a tether and satellite rebound at short range is a paramount safety concern.

Since the ejection velocity must be lower than 1.5 m/s for Shuttle safety considerations, a second analysis was done by setting the ejection velocity at the nominal 1.47 m/s (provided by the current SEDS ejection system) and by analyzing the sensitivity of the time from satellite ejection to the crossing of LV vs the ejection angle.

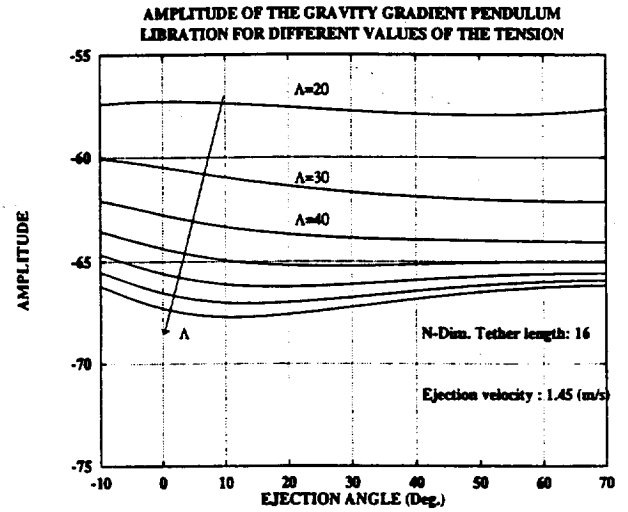
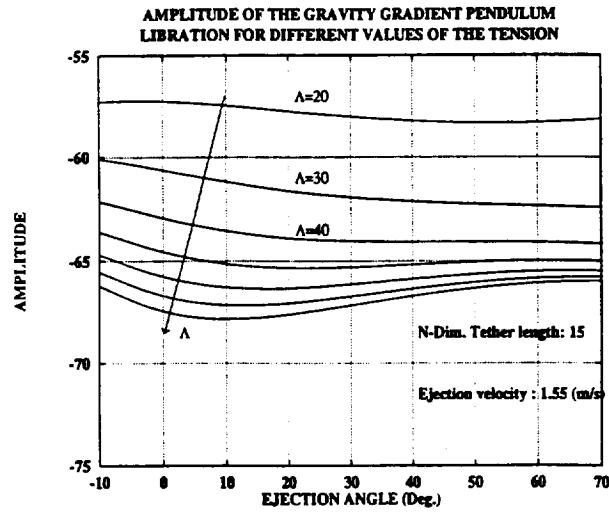
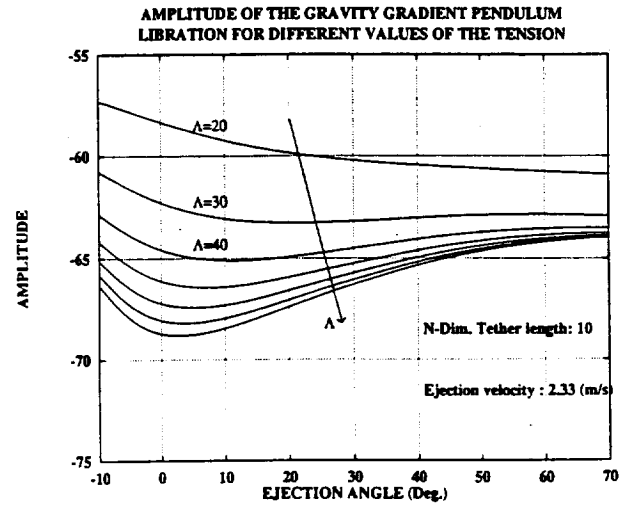
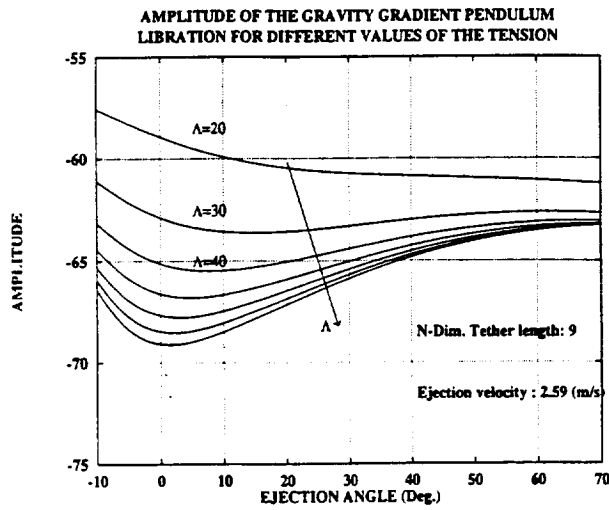
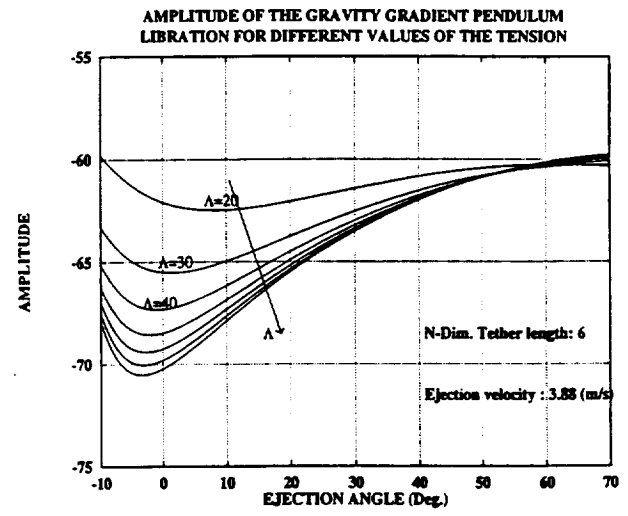
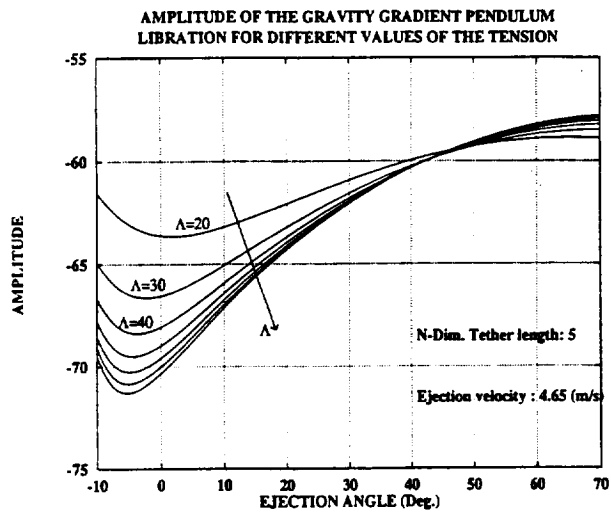
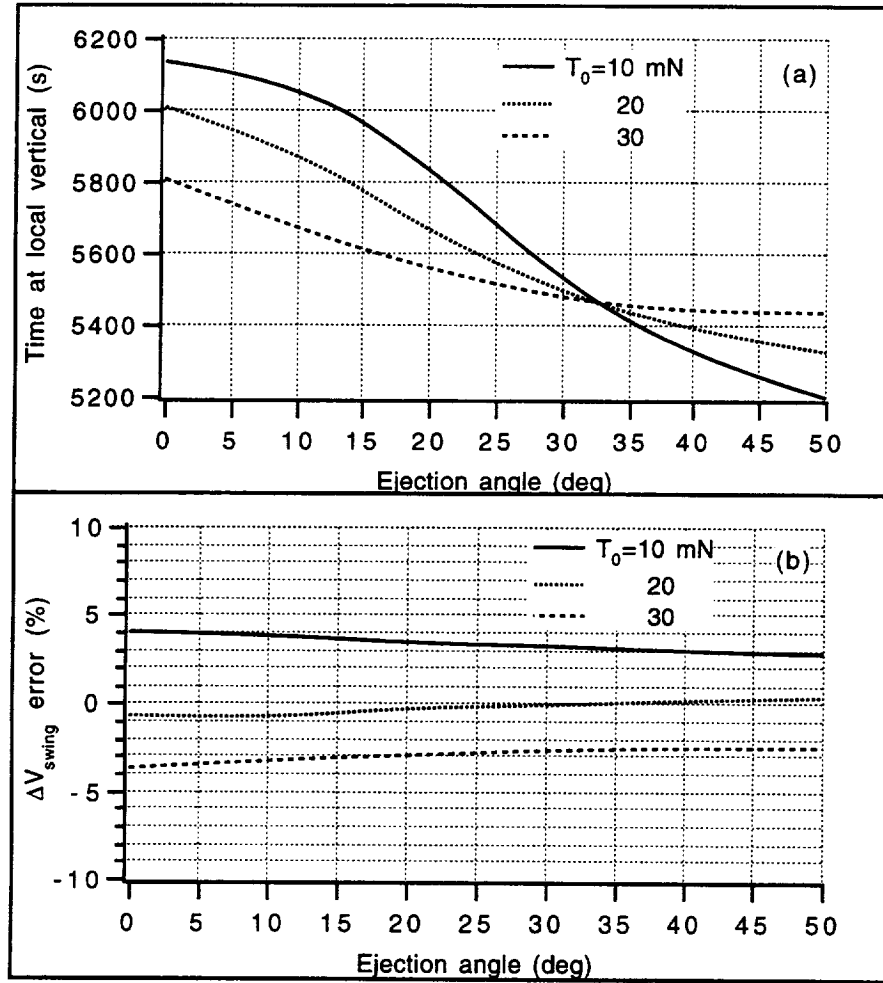


Fig. 7. Final libration amplitude vs ejection angle for different values of the non-dimensional minimum tether tensions and ejection velocities.



Figs. 8. Sensitivity of deployment maneuver to the ejection angle θ_0 of the satellite for $V_0 = 1.47$ m/s: (a) time of tether crossing LV and (b) percent error of ΔV_{swing} (see text) at LV crossing.

The results of this second analysis are summarized in Figs. 8 which show: (a) the time of the tether crossing LV vs the in-plane ejection angle θ_0 at the start of deployment for different values of T_0 and (b) the percent error of the ΔV_{swing} (the *swinging* component) at satellite release vs θ_0 . The error affecting the *hanging* component $L_{CM}\Omega$ in eqn. (8), which is not shown here, is usually negligible with respect to the error affecting the swinging component.

It is clear from Fig. 8(a) that the time of LV crossing is independent of the minimum deployer's tension T_0 for an ejection angle $\theta_0 \approx 32^\circ$ (differently from the convention used previously, the plus sign means in the forward direction). Moreover, the tether length is also independent of the static deployer's tension for $\theta_0 \approx 32^\circ$ (see Fig. 9). Consequently, preserving the timing to reach LV requires smaller ejection velocities than preserving the final libration amplitude (and ΔV at LV crossing). If the former solution is implemented the ΔV at LV will vary with a change of the minimum tension but the error affecting the ΔV is within the desired bounds for the expected range of minimum tensions. In conclusion, the braking phase should start as late as possible during deployment in order to preserve the stable timing of the overall deployment maneuver obtained through the previous selection of the initial conditions. It is readily seen from Fig. 9 that any braking action taking place after $t \geq 4000$ s would have a small impact on the time sensitivity of the maneuver.

The slowing down of the deployment velocity is accomplished by means of the non-linear control law developed for SEDS-II [11]. However, contrary to SEDS-II, this (late) braking phase has a very small effect on the libration angle, as it primarily affects the tether speed profile close to the end of deployment. The addition of the braking phase to the free deployment shifts slightly the value of θ_0 insensitive to T_0 from 32° to 31° which will be the value adopted from now on. Consequently, most of the deployment of SEDSAT is carried out without any active control and the brake is activated only in the last 16-20 km of deployed tether length solely for reducing the tether exit velocity to zero. The braking phase is accomplished with a feedforward-feedback control law which is robust with respect to variations of the deployer's friction parameters. The tether libration is minimally affected by this late braking phase whereas the insensitivity of the velocity vector and timing at release is provided by a suitable set of initial conditions at the start of deployment.

The reference profiles for the SEDSAT deployment control law were derived by imposing that the brake is activated for $t \geq 4000$ s (i.e., $L \geq 16$ km) with the following final state vector:

$$L = 20 \text{ km}, \quad \dot{L} = 0.1 \text{ m/s}, \quad \theta = 0, \quad \dot{\theta} = 0.09 \text{ deg/s}.$$

The final libration speed was weighted very lightly in the cost function of the optimization procedure [9] because, as previously mentioned, it is no longer dependent on the braking action but rather on the initial conditions at satellite ejection.

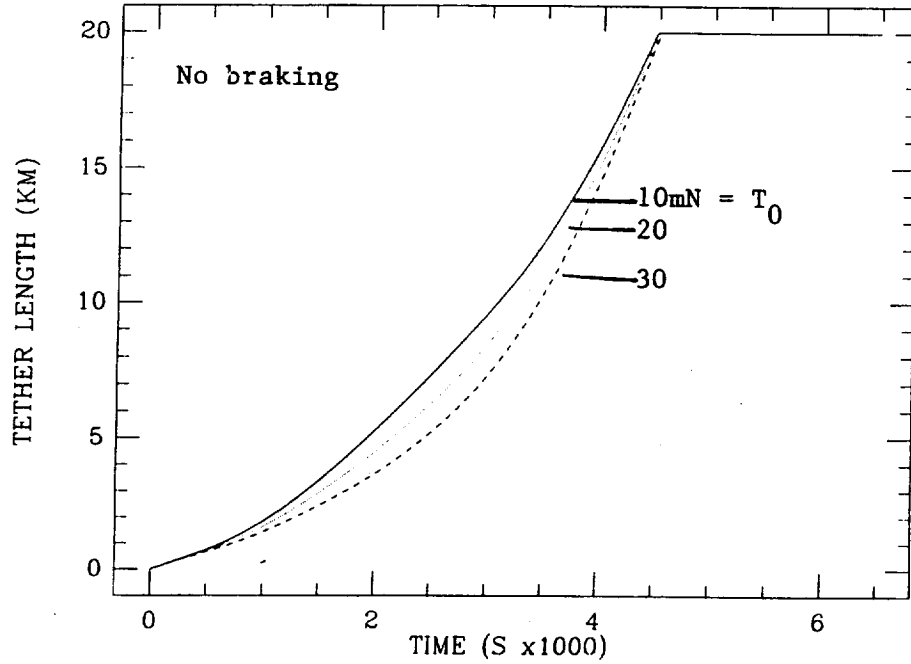


Fig. 9. Tether length vs time for different static tension values (no braking).

The initial conditions at ejection are as follows:

$\theta_0 = -31^\circ$ (upward and forward) and $V_0 = 1.47$ m/s.

Because of a slight increase of the SEDSAT satellite, a mass = 34 kg is adopted in deriving reference profile 39. Also the feedback gains are $k_1 = 0.002$ and $k_2 = 0.2$ (like in SEDS-II) in order to limit the reaction of the control law to the sling/scrub transition. The brake is activated at $t = 4000$ s ($L \approx 16$ km) and the reference value of the minimum tension is 20 mN. The value of $\Delta V_{CM,H}$ at LV crossing is 32 m/s which corresponds to a final libration amplitude of about 63° . By adding the hanging component ΩL_{CM} , the total ΔV at release is 53 m/s. The deployment dynamics is shown in Figs. 10(a)-10(f). The ΔV and the timing at LV crossing are now insensitive to variations of the minimum deployer's tension. The magnitude of the ΔV at release is sufficient for reaching the desired apogee height.

Reference profile 39 and the parameters of the associated control law are summarized in Appendix A of this report.

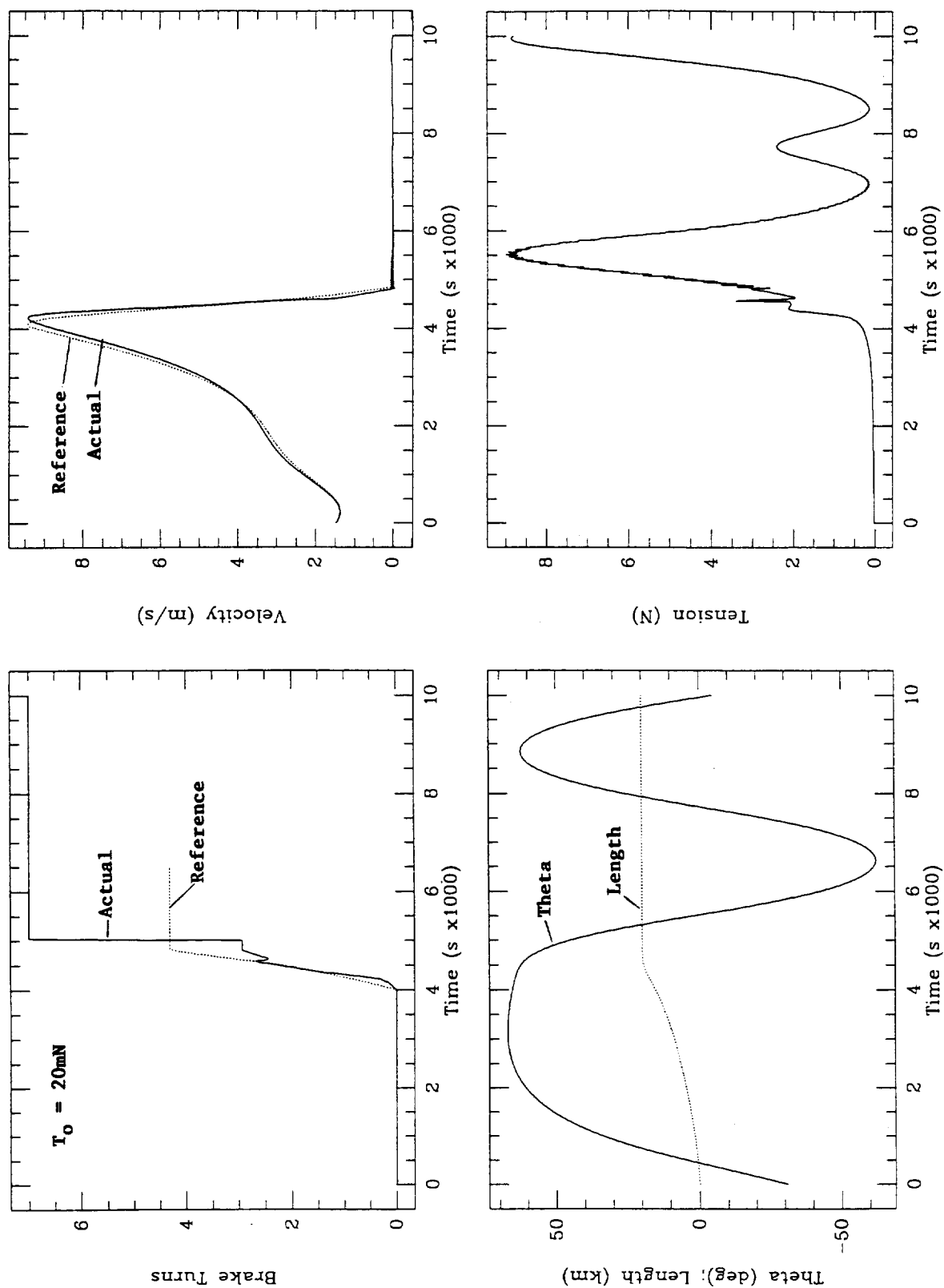


Fig. 10(a). Dynamic response of SEDSAT during deployment for reference 39 (see text).

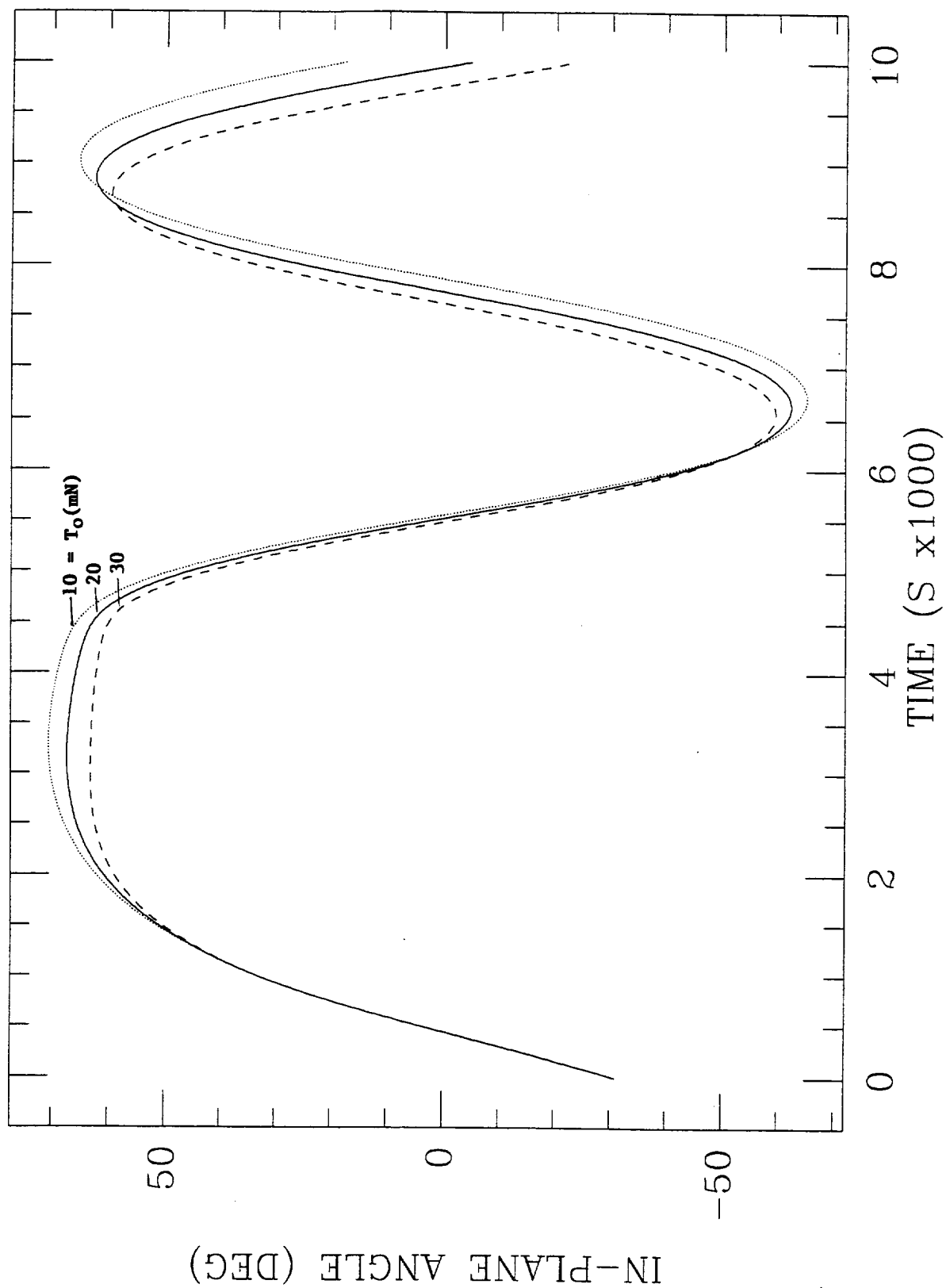


Fig. 10(b). Dynamic response of SEDSAT during deployment for reference 39 (see text).

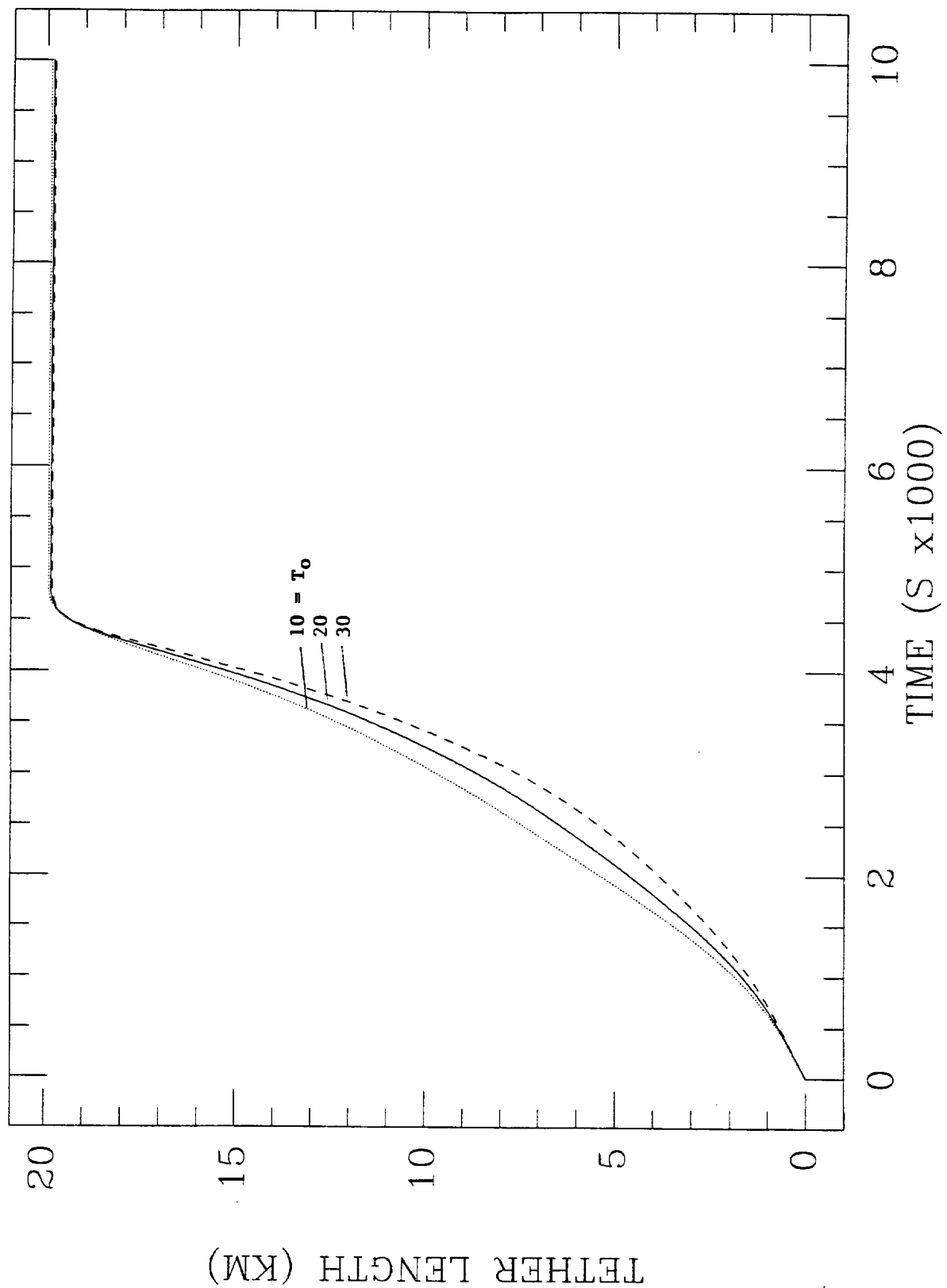


Fig. 10(c). Dynamic response of SEDSAT during deployment for reference 39 (see text).

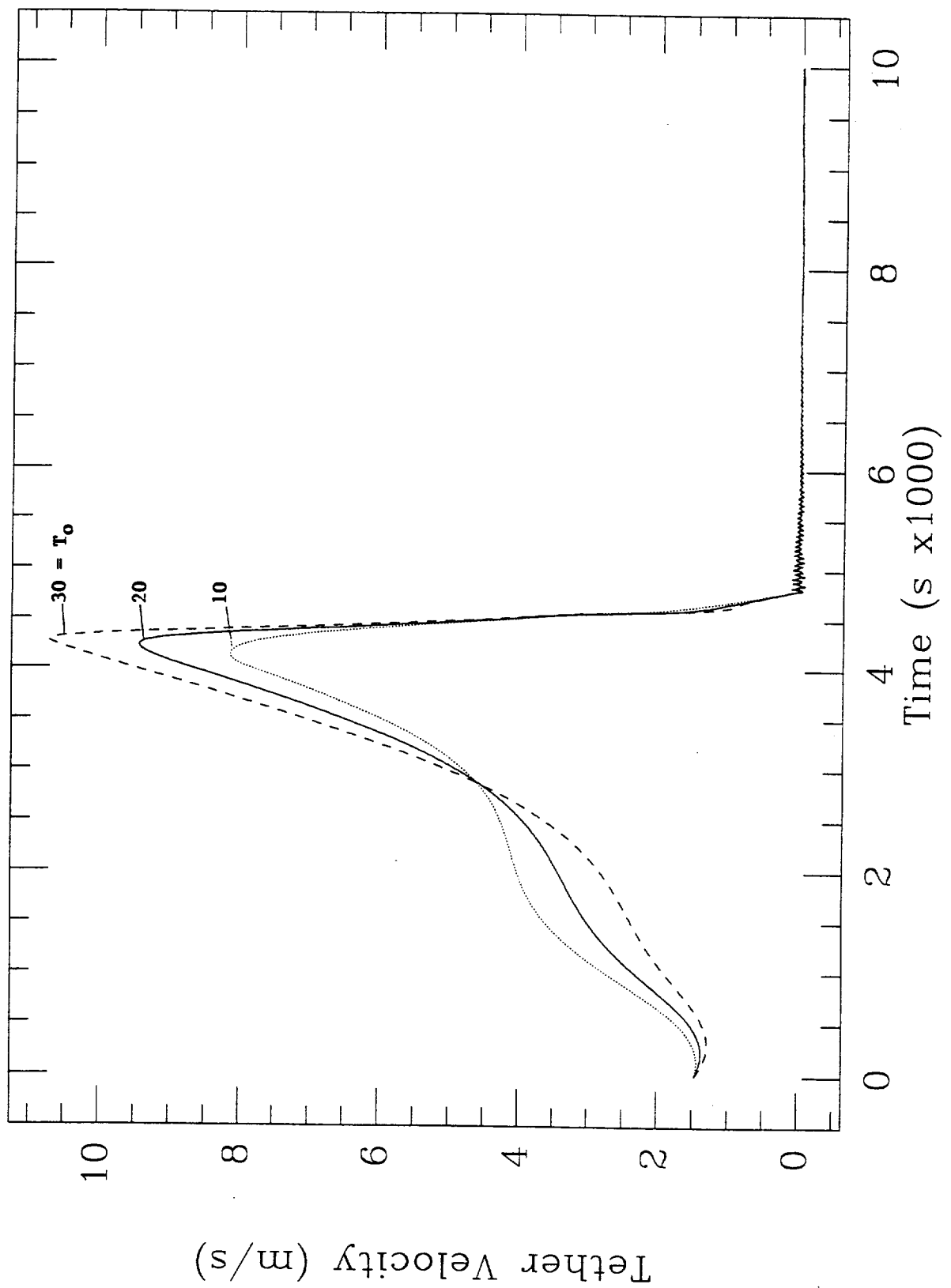


Fig. 10(d). Dynamic response of SEDSAT during deployment for reference 39 (see text).

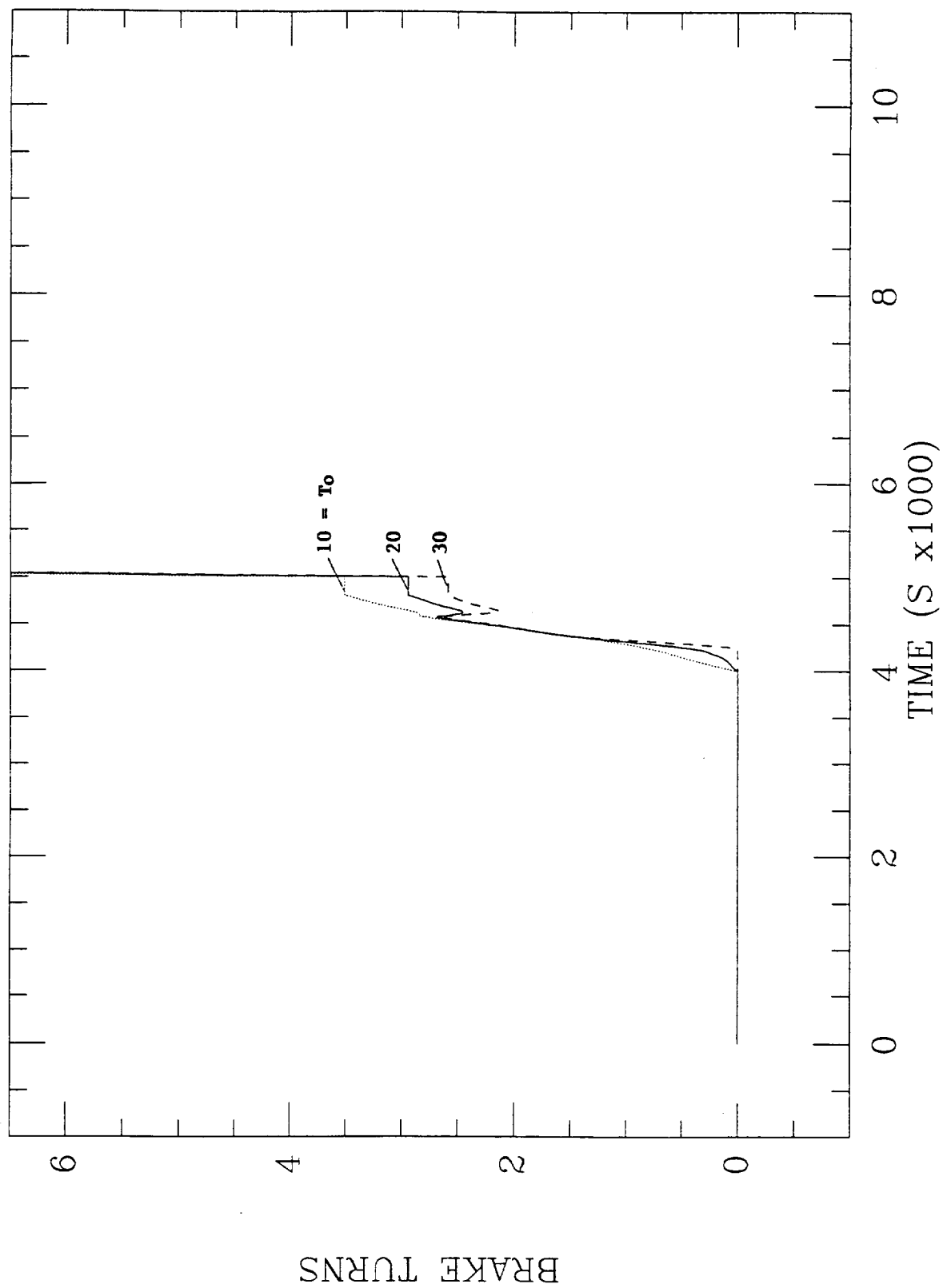


Fig. 10(e). Dynamic response of SEDSAT during deployment for reference 39 (see text).

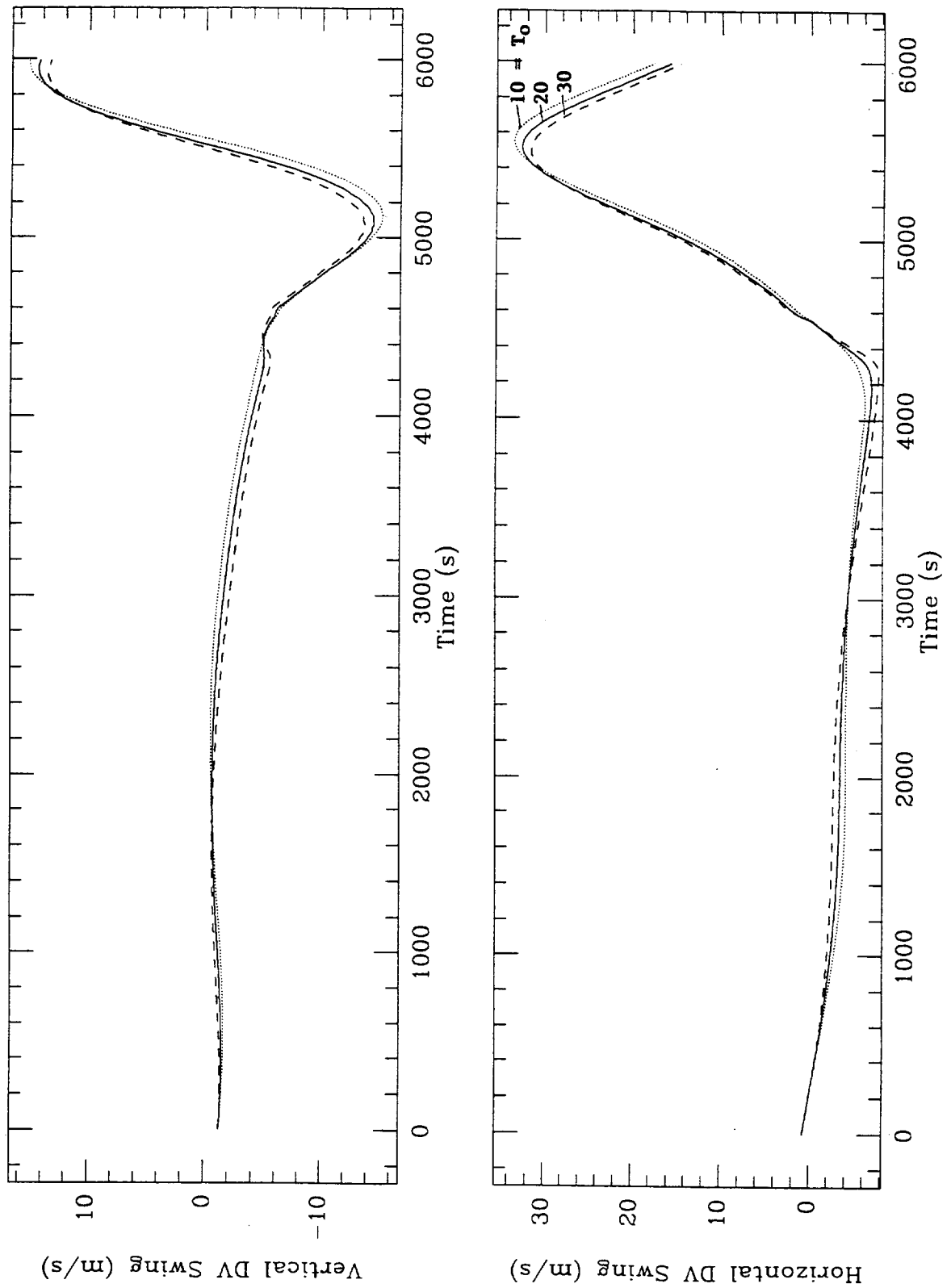


Fig. 10(f). Dynamic response of SEDSAT during deployment for reference 39 (see text).

The nominal post-release orbit of the center of mass of the satellite-tether system is about 317kmX535km, with respect to a spherical Earth, after the first tether cut at the Shuttle end. Subsequently, close to a convenient apogee, the tether is cut a second time at the satellite end in order to raise the altitude of the perigee. The tether accounts for about 17% of the mass of the satellite-tether system and its release provides an increase of perigee height of about 13 km after considering that L_{CM} in this case is the distance between the satellite CM and the CM of the satellite-tether system and that the tether is not exactly at apogee when crossing LV for the second time.

In conclusion, the final nominal orbit of the satellite is about 330kmX535km with respect to a spherical Earth. When the apogee altitude is computed with respect to an oblate Earth, its numerical value can vary by about ± 9 km with respect to the number quoted above depending on the value of the argument of perigee. With this control law the final tether length of 20 km is reached in 1 hour 20 min while the tether crosses the local vertical 12 min later. Consequently, the satellite with the attached tether is released 5,520 s after the start of deployment from the Shuttle.

The absolute time of the first cut (or equivalently the orbital anomaly) is not critical for SEDSAT because there is no specific requirement on the phase of the final orbit for this mission. However, the sensitivity of the release time to variations of the deployer's model parameters can be more or less important depending on the level of crew and on-board equipment involvement in estimating the tether crossing LV. In the simplest scenario, the LV crossing could be based solely on the deployment start time and, consequently, the insensitivity of the maneuver duration to different deployer's parameters is important for obtaining an accurate ΔV at release. For instance, the timing error associated with the expected variability of the static tension is less than ± 20 s.

The hydraulic component (proportional to \dot{L}^2) in the deployer's tension model also has an effect on the deployment dynamics and, hence, on the timing and magnitude of ΔV at the crossing of LV. Unfortunately, the ejection angle that nullifies the effect of the hydraulic tension term is on the opposite side of LV with respect to the ejection angle that nullifies the effect of the minimum tension. It can be inferred from Figs. 11(a)-11(b), which show the deployment dynamics for reference profile 39 for different values of the hydraulic tension term, that a variation of the inertia multiplier I of $\pm 25\%$, with respect to the reference value of 4.1, involves a variation of the timing to cross LV of about ± 80 s. The variation of the horizontal component of the swinging ΔV is less than ± 1 m/s at the

estimated time of LV crossing. The variation of the vertical component of the swinging ΔV is about ± 4 m/s at the estimated time of LV crossing. However, a vertical ΔV produces an increase (or decrease) of the orbital height which is about 1/4 of the effect produced by an horizontal ΔV .

In summary, if the tether cut is determined by the estimated time to cross LV from the start of deployment, the dispersion of the horizontal ΔV component is minimized. If the same tether cut is effected at the actual crossing of LV, the dispersion of the vertical ΔV component is minimized. The latter case requires more crew and on-board equipment involvement. The two cases produce comparable dispersion in terms of the height of the final orbit. The former case can produce a slightly different phasing of the initial and final orbit which, however, is not an issue for SEDSAT at present.

The time accuracy at release is definitely important for future missions which are expected to use a SEDS-type deployer for the atmospheric reentry of capsules. In this case the dispersion on the absolute time at release determines to a large extent the dispersion of the reentry capsule footprint. For instance, a timing error of the reentry ΔV in LEO of ± 20 s implies, approximately, a ± 148 km (± 80 nmi) error in the length of the footprint. It is worth remembering that the length of the footprint of the *Gemini* capsule was typically ± 185 km (± 100 nmi) [12].

1.5 Conclusions on SEDSAT Control and Dynamics

In 1997, SEDSAT will be deployed on a 20-km-long tether from the Shuttle orbiting on a 297-km circular orbit and released at the time the tether crosses the local vertical. The final tether length is reached in 1 hour 20 min with the deployment control law described in this report. Upon crossing the local vertical, 12 min later, the tether is cut at the Shuttle and, consequently, the satellite with the attached tether is injected into an higher orbit thanks to the librating tether acting as a sling shot. After the (second) tether disconnection from the satellite, close to apogee, a final orbit of about 330kmX535km, with respect to a spherical Earth, is reached. The present estimate for SEDSAT lifetime is approximately 3 years.

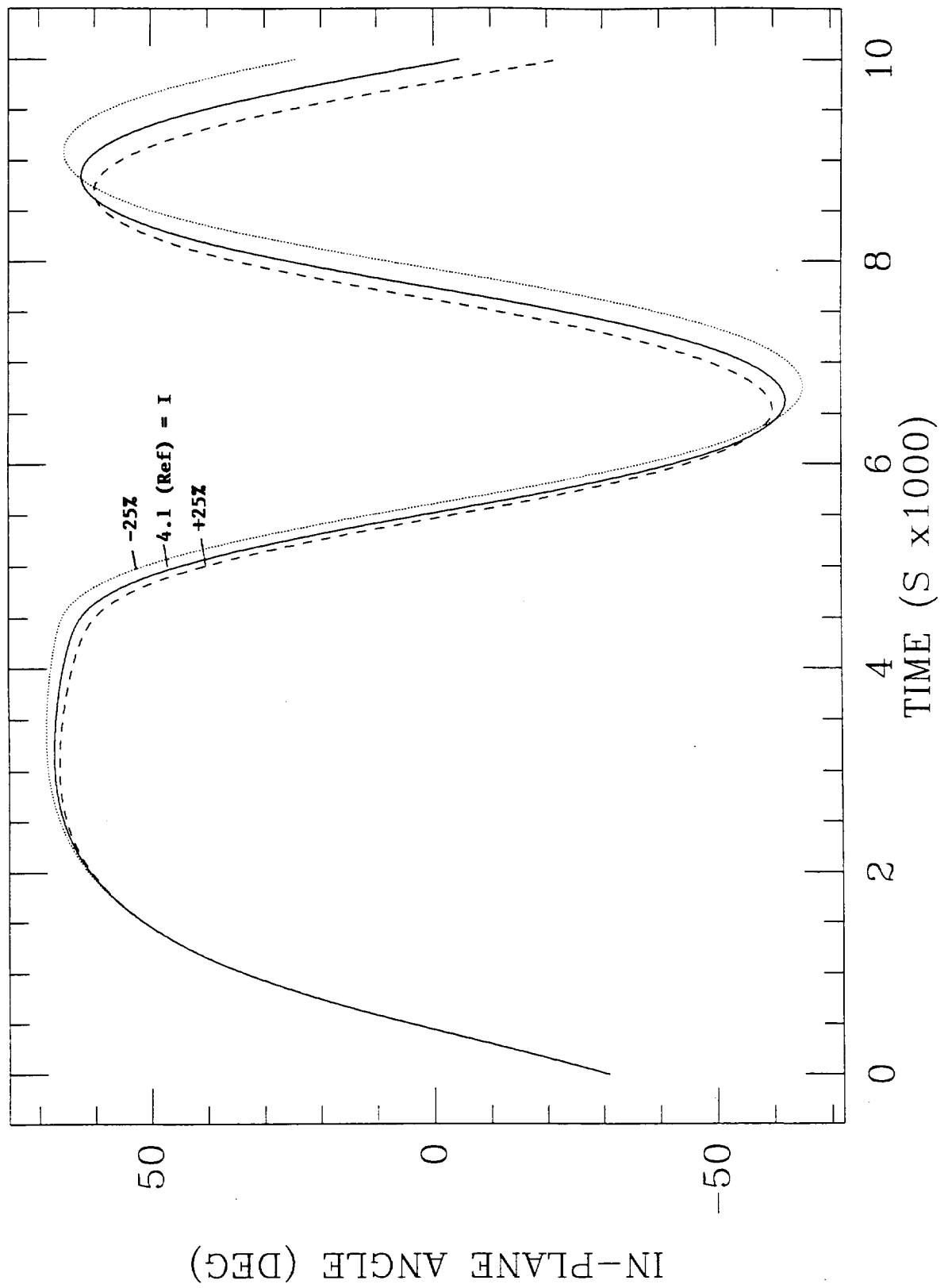


Fig. 11(b). Sensitivity of deployment to Inertia Multiplier I for reference profile 39.

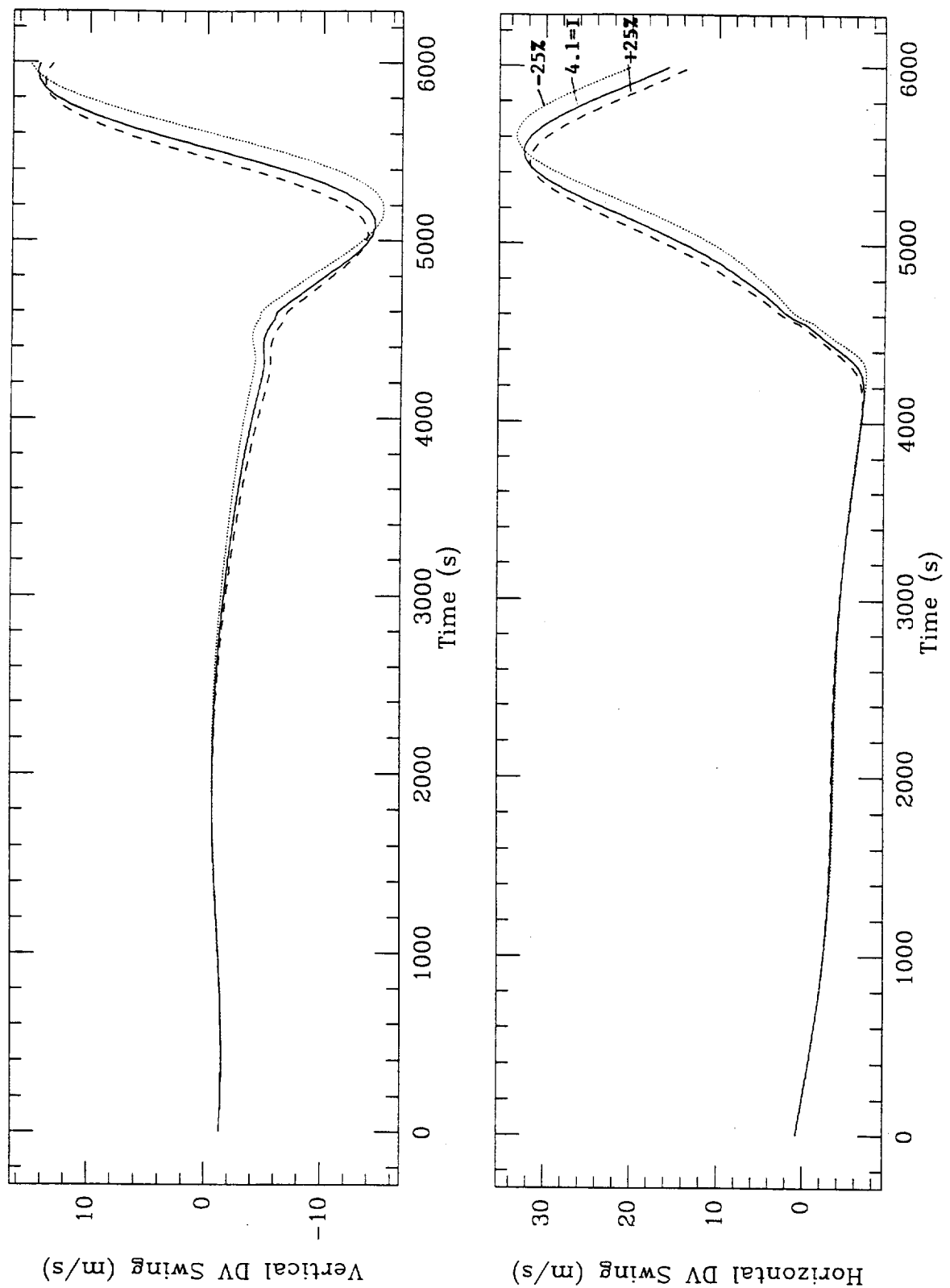


Fig. 11(b). Sensitivity of deployment to Inertia Multiplier I for reference profile 39.

2.0 Tethered Multi-Probe for Thermospheric Research

In the following we include three papers, authored by scientists of the Smithsonian Astrophysical Observatory, that were presented to the *Fourth International Conference on Tethers in Space* which illustrate respectively: (1) the chemistry of the lower thermosphere and the associated cooling processes; (2) the on-board instrumentation required to conduct the measurements of the cooling processes; and (3) a possible tethered system to carry out those measurements in the altitude range of 110-160 km for the lowest probe and 200-250 for the mother platform.

The cooling processes in the mesosphere and in the lower thermosphere are of particular scientific and also public interest because, according to several scientists, they are related to the increased concentration of "greenhouse gases" in the troposphere and hence to the global warming trend of the troposphere. A tethered system with one or preferably two probes attached to typically a 90-km-long tether linked to a mother platform can uniquely contribute to this exciting field by taking measurements in a region of the Earth's atmosphere that is not accessible to conventional satellites.

Paper MFUTMS-1

**ATMOSPHERIC SCIENCE WITH TETHERS: HEATING, COOLING AND
CHEMISTRY IN THE LOWER THERMOSPHERE**

Kate P. Kirby
Smithsonian Astrophysical Observatory

**Fourth International Conference on
Tethers in Space**

Sponsored by National Aeronautics and Space Administration, Smithsonian
Astrophysical Observatory, Agenzia Spaziale Italiana, Martin Marietta,
Alenia Spazio S.p.A., Science Applications International Corporation

Smithsonian Institution, Washington, DC, 10-14 April 1995

ATMOSPHERIC SCIENCE WITH TETHERS; HEATING, COOLING AND CHEMISTRY IN THE LOWER THERMOSPHERE

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Abstract

Tethered probes offer a unique opportunity for studying the lower thermosphere and ionosphere. An instrument package focussed to provide detailed information on the various cooling processes taking place throughout the thermosphere would enable significant progress in the overall understanding of the energy budget in this region. Cooling processes, intimately linked to the atmospheric chemistry, may be substantially affected by the build-up of greenhouse gases in the atmosphere. Evidence for increased cooling in the upper atmosphere might serve as an early diagnostic of global warming occurring in the lower atmosphere. Enhanced cooling in the upper atmosphere may contribute to increased ozone destruction.

Introduction

It is an honor to lead off the session on future missions with tethered satellites. It is clear that the opportunities offered for atmospheric science by a tethered instrument package are particularly compelling:

- 1) The altitudes which can be probed by *in situ* techniques, down to 120 km, are in great need of exploration.
- 2) The idea of flying smaller, less expensive missions with instrument packages that target important questions but that do not attempt to address all the science has the advantages of flexibility - with faster realization from proposal and design to actual flight.
- 3) The advantage of multi-probe tethers, in which a number of identical instrument packages are strung out, like pearls on a string, offers a unique opportunity to obtain properties in the atmosphere simultaneously at several different altitudes.

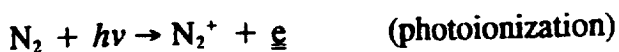
It has been noted that, "*the Earth's mesosphere and lower thermosphere are the least explored regions in the Earth's atmosphere*".¹ These regions span the altitude range from 60 km to 130 km. Too high to be explored by balloon-borne instruments and too low to be explored *in situ* by satellites, this region of the atmosphere is often referred to as the "ignorosphere".

The purpose of this talk is twofold. First, critical questions are raised regarding cooling processes in the lower thermosphere and mesosphere. It will be shown that these processes are intimately connected to an understanding of the atmospheric chemistry and overall energy budget in these regions. Secondly, it is emphasized that an understanding of cooling processes in the upper atmosphere has direct relevance to two important global change issues: global warming due to the build-up of greenhouse gases from anthropogenic sources, and stratospheric ozone depletion.

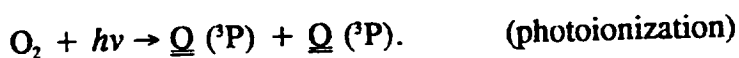
Several other papers in these proceedings are complementary to this one. In his paper, "*Spectroscopic Measurements from a Tethered Satellite Platform (WSCI-5)*", Dr. Kelly Chance has described the specific series of measurements which we propose to make to study the cooling mechanisms and has defined the kind of instrument package we are considering. Dr. Enrico Lorenzini and co-workers have described the tether engineering and orbital considerations required for such an atmosphere science mission in their paper, "*Tethered Multi-probe for Thermospheric Research (Th FUTA-6)*".

Heating, Cooling and Chemistry: An Overview

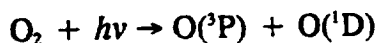
Heating of the upper atmosphere occurs primarily through the absorption of solar radiation at ultraviolet and extreme ultraviolet wavelengths and is mediated by collision between electrons, ions, and neutrals.² The process of heating puts energy into the translational degrees of freedom of the gas. This can be done directly by the absorption of radiation to produce fragment species with high kinetic energies - as in photoionization and photodissociation. Examples are given, with the translationally hot species underlined:



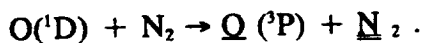
and



Heating can also be accomplished indirectly by the absorption of radiation to produce electronically or vibrationally excited species which then collide, converting their internal energy into translational energy of the collision partners. This collision process is called quenching. An example is the photodissociation of molecular oxygen to produce an electronically excited oxygen atom which collides with N_2 to heat the gas, in the process de-exciting the oxygen atom



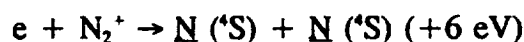
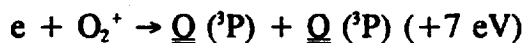
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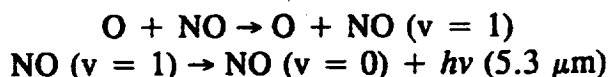
Electronically excited species which are metastable, such as $\text{O} (^1\text{D})$, have much greater

chemical reactivity than ground state species. With increasing translational energy ground state species such as N(⁴S) and O(³P) become much more chemically reactive because they are able to surmount small endothermicities on the reaction surface. Thus it is clear that absorption of radiation and the consequent heating are primary drivers of the chemistry in the thermosphere.

Even at night time, with no solar radiation present, heating processes such as dissociative recombination occur. Dissociative recombination, the primary electron loss mechanism in the lower thermosphere and ionosphere, takes place when an electron is captured by a molecular ion and the resulting neutral molecule dissociates. Significant kinetic energies can be imparted to the fragments in the process, thereby heating the neutral gas. Examples include:



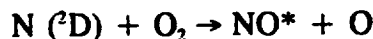
Cooling takes place when kinetic energy of the gas is transformed through collisions into internal energy which can then be radiated away to space. An example is the excitation of the $v = 1$ vibrational mode of NO by collisions with atomic oxygen. The NO then radiates away this energy in the fundamental band ($v = 1 \rightarrow 0$) at $5.3 \mu\text{m}$:



Nitric oxide is thought to be the major coolant from approximately 120 to 200 km. It is to be noted that the major molecular species in the atmosphere, N_2 and O_2 , are not infrared active. Therefore cooling is predominately accomplished through trace species, such as NO and CO_2 .

There are strong interconnections between the chemistry and heating and cooling processes which can be best illustrated by an example. It is impossible to show, given the time and space allotted, the full range of the complex chemistry which takes place in this region of the atmosphere, with just four major neutral ingredients: N_2 , O_2 , O and He. The following examples are just two out of the five or more major chemical reactions forming the NO molecule:

- 1) An electronically excited nitrogen atom can react with molecular oxygen to produce NO molecules that are vibrationally excited.

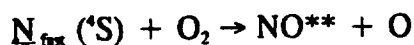


From laboratory experiments it is known that NO is formed in a range of vibrational states up to $v = 12$.³ If NO^* radiates away the vibrational energy (predominately via $\Delta v = 1$ transitions) NO contributes to cooling. If the NO^* is quenched before it radiates, the energy goes into heating the gas, and the formation of NO then results in net heating.

The factors determining whether NO formation results in heating or cooling are: 1) the densities at the altitude at which NO is formed (densities determine the frequency of

collisions and thus the quenching rate); and 2) the radiative transition probabilities or Einstein A-coefficients for radiation of the vibrational energy.

2) Another mechanism for NO formation involves translationally hot nitrogen atoms which react with molecular oxygen to produce NO which is vibrationally and rotationally excited.⁴



It turns out that it matters whether internal energy is manifested as vibration or rotation because the transition probabilities differ by several orders of magnitude. Vibrational transition probabilities are typically almost a thousand times larger than rotational transition probabilities. Thus energy deposited in vibration is more easily radiated, thereby contributing to cooling, whereas energy deposited in rotation is not as easily radiated and may contribute to heating.

Thermospheric/Mesospheric Cooling Processes

The primary cooling processes in the thermosphere and ionosphere are summarized here. Above about 200 km, the oxygen fine-structure transition $O(^3P_1) \rightarrow O(^3P_2)$ which radiates at $63 \mu\text{m}$ is the major cooling mechanism. The fine structure levels of atomic oxygen are thermally populated. Between approximately 120 to 200 km, the fundamental band ($v = 1 \rightarrow 0$) of NO, radiating at $5.3 \mu\text{m}$, is the major cooling mechanism. Below approximately 120 km the v_2 vibrational bending mode is the predominant coolant, radiating at $15 \mu\text{m}$. The CO_2 is excited by collisions with atomic oxygen.

There are major uncertainties, however, regarding these mechanisms. Thus a tether probe instrument package targeted to measure spectroscopic emission of the major coolants has tremendous potential.

The NO density is not well-known, with some models disagreeing with others by as much as an order of magnitude. The formation mechanisms for NO are still in some doubt. Is the cooling accomplished primarily by $v = 1 \rightarrow 0$ transitions excited by collisions with atomic oxygen, or does the chemistry contribute substantially to the cooling via $\Delta v = 1$ transitions of higher-lying vibrational levels populated in the formation process ($v = 4 \rightarrow 3, 3 \rightarrow 2, 2 \rightarrow 1$, etc.)?

The CO_2 density is not well-known in the lower thermosphere and ionosphere. The rate coefficient for the excitation of the v_2 bending mode of CO_2 by collisions with atomic oxygen is very uncertain. There is a factor of 6 difference between measurements carried out in the laboratory and emission measurements made in the atmosphere.^{6,7}

There may be additional cooling mechanisms involving other constituents that have not been considered. For instance, recent data from a rocket experiment (CIRRIS) indicate a significant presence of vibrationally excited CO which had not been seen previously. This may contribute to the cooling. Other recent data show both neutral molecules and molecular ions with

much greater vibrational and rotational excitation than expected.⁸ The molecular ion N_2^+ was found to have as much as 0.5 eV of vibrational and rotational excitation.

Ultimately, if one could obtain some data down around 90 km and below, one might get closer to solving one of the greatest mysteries regarding the thermal budget of the Earth's atmosphere: the Mesospheric Temperature Anomaly. Whereas at 200 km temperatures may reach 1500 to 2000° K, only 100 km lower at the mesopause (85-90 km) the coldest temperatures in the Earth's atmosphere exist (~130° K). The high temperatures are understood, but the precipitous drop to the very low temperatures at the mesopause remains to be adequately explained. A clear understanding of the various cooling processes in the lower thermosphere will help to explain this phenomenon.

Cooling and Global Change

Cooling processes in the upper atmosphere are linked to two prominent global change issues. A brief review of both the global warming and ozone depletion problems follows.

The Earth's atmosphere, which is approximately 80% N_2 and 20% O_2 , is transparent to much of the solar radiation in the 3200 to 7000 Å region of the spectrum. This solar radiation is largely absorbed by the Earth. In order for the Earth to stay in equilibrium it must reradiate this energy, and since it is at a lower temperature than the sun it radiates at longer wavelengths, in the infrared. Certain molecules such as H_2O , CO_2 , CH_4 and the chlorofluorocarbons in the atmosphere absorb this infrared radiation, trapping it and causing the earth's surface and lower atmosphere to heat up. This additional amount of heating makes the Earth habitable for plant and animal life. But increasingly gases, such as carbon dioxide from the burning of fossil fuels and methane from agriculture and raising livestock, are being put into the atmosphere in abundance. These gases will trap more radiation, causing the temperature in the lower part of the atmosphere (the troposphere) to rise. What is known as "Global Warming" results.^{9,10}

Extrapolation of recent trends in measured CO_2 and CH_4 concentrations in the atmosphere predicts a worst-case scenario of CO_2 and CH_4 concentrations doubling over the next century.

For a doubled CO_2 and CH_4 atmosphere large computer codes known as General Circulation Models (GCM's) have predicted that temperatures in the lower atmosphere (0 to 15 km) will rise by approximately 1.5 to 4.5° K over the next century. However above 15 km, in the stratosphere, mesosphere, and thermosphere the temperature is not raised but instead is lowered. In the stratosphere, temperatures are predicted to decrease by 6-8° C and in the thermosphere the temperature decreases may be as much as 40-50° C.^{11,12} This effect is all due to the fact that CO_2 acts as a heat trap in the troposphere and as a coolant throughout the upper atmosphere. Thus significant increases in the CO_2 density cause heating in the lower atmosphere and cooling in the upper atmosphere. The extent of the cooling predicted depends critically on the rate coefficient for the $O + CO_2$ excitation of the v_2 bending mode of CO_2 - a parameter which is very uncertain. However, the measurement we propose to undertake with the tether would enable us to quantify this process very accurately.

The predicted magnitude of the temperature decrease in the thermosphere is larger by over

an order of magnitude than the predicted increase in the lower atmosphere that defines the "global warming" problem. If this large temperature decrease could somehow be monitored it could serve as an early detection of global warming beginning in the lower atmosphere - where the effect is much more subtle and therefore difficult to measure. There is some evidence that considerably lower temperatures are already occurring in the mesosphere.^{13,14,15}

Cooling of the middle atmosphere, though not as profound as the upper atmosphere, will significantly affect the ozone chemistry. Lower temperatures in the stratosphere may increase the frequency of formation of polar stratospheric clouds that drive the heterogenous chemistry and causes massive destruction of the ozone over Antarctica during the transition from polar winter to spring. Other ozone depletion chemistries taking place on the surface of sulfate aerosols may also be enhanced by lower temperatures. Thus, significant temperature decreases resulting from a build-up of CO₂ may further exacerbate ozone destruction. Ozone, itself, is the dominant heat source in the lower stratosphere. Decreasing the amount of ozone will drive temperatures still lower. Unfortunately, these two effects operate together to further increase ozone depletion. Hence, the effect of the build-up of CO₂ may be far more serious in the middle and upper atmospheres than in the lower atmosphere.

CONCLUSIONS

In summary, there are many unknowns regarding the cooling processes in the lower thermosphere which could be explored with a tethered probe and which have important implications for understanding several critical global change issues.

ACKNOWLEDGEMENTS

I would like to thank my atmospheric chemistry collaborators in this effort, Dr. K. Chance, Prof. A. Dalgarno, Dr. P. Smith, and Dr. R. Sharma. In addition, I thank the tether group at SAO, including Dr. E. Lorenzini, Dr. M. Grossi, and Dr. M. Cosmo. Finally, I would like to acknowledge Prof. I. Shapiro, Director of Harvard-Smithsonian Center for Astrophysics, who brought our groups together.

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Paper WSCI-5

**SPECTROSCOPIC MEASUREMENTS FROM A TETHERED SATELLITE
PLATFORM**

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**Fourth International Conference on
Tethers in Space**

Sponsored by National Aeronautics and Space Administration, Smithsonian
Astrophysical Observatory, Agenzia Spaziale Italiana, Martin Marietta,
Alenia Spazio S.p.A., Science Applications International Corporation

Smithsonian Institution, Washington, DC, 10-14 April 1995

SPECTROSCOPIC MEASUREMENTS FROM A TETHERED SATELLITE PLATFORM

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Abstract

Spectroscopic measurements of atmospheric emission that can be made from a tethered instrument module are potentially important as direct probes of lower thermospheric and mesospheric cooling and related chemistry. Cooling of the lower thermosphere and mesosphere is closely related to "greenhouse" warming of the lower atmosphere (the troposphere) and may provide an early indication of such warming. This paper presents an instrument concept for a limb-observing spectrometer that would be combined with one or more *in situ* neutral mass spectrometers to perform definitive measurements of all necessary components of the major cooling processes in the lower thermosphere and mesosphere. Spectroscopic emissions would be monitored looking to the Earth's limb to measure the emitted radiation strongly peaked at a range of tangent altitudes at and below the instrument package containing the spectrometer. The instrument candidates for the proposed measurements have good technical heritage although, as noted below, they vary in complexity and in requirements on satellite resources. They are briefly described, followed by notes on the issues of cooling and pointing and description of a straw man instrument package

Introduction

A tethered satellite system provides a unique opportunity for obtaining measurements in the Earth's lower thermosphere and mesosphere that are complete and definitive in the known processes that control cooling in this part of the atmosphere. The scientific issues that drive the selection of the tether satellite instrument described in this paper are discussed in detail by my colleague Dr. K. Kirby elsewhere in these proceedings.¹ The tethered satellite concept used here is also from a Center for Astrophysics presentation in these proceedings, by E. Lorenzini *et al.*² This part of the atmosphere is difficult to measure in detail because it is well above altitudes that can be explored using balloons or aircraft and below that normally accessible with satellites. Limited measurements have been made using rockets³ and limb instruments on the space shuttle.⁴ However, these have not been able to determine diurnal and latitudinal variations of emission and absolute concentrations of the emitting species. The straw man tethered satellite concept used here consists of an upper platform with a 200 km \times 250 km orbit with two tethered probes separated by 5 km and an overall tether length of 90 km.² The proposed measurements would include spectroscopic measurements of limb emission, using a spectrometer system developed by the Harvard-Smithsonian Center for Astrophysics, in conjunction with two *in situ* neutral mass spectrometers provided by investigators at another institution (for example, as described in References 5-7).

Proposed Experiment

- 15 μm CO_2 (atmospheric cooling and pointing)** This is a primary measurement of atmospheric cooling. Below about 120 km, infrared emission by CO_2 , which has been excited by collision with oxygen atoms, is the dominant cooling mechanism in the thermosphere. In the lower atmosphere, various minor isotopic species and hot bands contribute to the radiance, but above about 105 km only the $01^{10} \rightarrow 00^00$ band is significant. Also note that above about 110 km the limb radiance becomes optically thin. The appropriate detector technology to use in this CO_2 band is HgCdTe operating at 80 K or less. A small linear array of detectors (the SAFIRE instrument proposed a 7×15 array) with a monochromator of modest size would be adequate. An additional 15 μm channel will measure lower altitude CO_2 for pointing of the limb spectrometers (see **Pointing**, below).
- 5.3 μm NO (atmospheric cooling)** The cooling lines include both the fundamental band of NO and vibrational hot bands. The best possibility for measurement is a diode-array based spectrometer using a linear array of HgCdTe detectors cooled to 80 K or less. A 200-element array of HIRDLS or AIRS-type detectors operating at 60 K, for example, would be quite adequate. An instrument measuring from about 4.17-6.25 μm could measure both the NO and the 4.3 μm CO_2 emission mentioned below with resolution which should be adequate to distinguish the overall rotational structure. An alternate approach would be the use of a single detector and a circularly-variable filter (as used in SPIRE³). A tradeoff study will need to consider sensitivity vs. the desire to resolve the (non-LTE) rotational structure of the bands to some extent.
- 4.3 μm CO_2 (diagnostic)** Measurement of the $30^01 \rightarrow 30^00$ bands permits the monitoring of CO_2 density in the solar-illuminated portion of the orbit. These measurements could be made with the same monochromator and detector array as 5.3 μm NO measurements.
- 63 μm O^3P (atmospheric cooling)** This measurement is more ambitious than the others included here. Although the technical heritage is sound, it would require both a more complex instrument (a metal-mesh Fabry-Perot) and liquid helium-temperature cooling (either from liquid helium or from a multi-stage Stirling/Joule-Thomson mechanical cooler. The best way forward with the spectrometer technology would be to include the group at NASM who have been involved with the long-wavelength spectrometer of ISO, and who have a flight spare of the (fully space-qualified) ISO Fabry-Perot in their possession.

Detector and instrument cooling Space qualified Stirling cycle coolers are available which supply 800 mW of cooling at 80 K from 30-35 W input power, operating from -20 to +40 C, and weighing 4.5 kg. Two-stage versions cooling to as low as 30 K are almost space qualified. They supply somewhat less cooling power at just about double the weight and power. Mechanical coolers operating to 4 K are under development. These coolers use a multi-stage Stirling/Joule-Thomson arrangement and give ca. 10 mW of cooling power at 4.2 K for 160 W of input power. Their weight is 16.5 kg. For near-term considerations, the 80 K coolers are a reasonable choice; the 4 K coolers are probably not. Other cooling possibilities for 80 K and below include the two-stage coolers, dewars with liquid nitrogen (77 K), pumped (solid) nitrogen (about 55 K) and solid H_2 (14 K) or Ne (25 K). For a short-term (several day) deployment, liquid helium cooling of the gallium-doped germanium photoconductor detector for the O^3P measurements and pumped (solid) nitrogen cooling of the HgCdTe detectors is the baseline.

Pointing Pointing for limb emission measurements should be accurate and stable to better than 1° . A horizon sensor detecting CO_2 at 40 km, operating at $15\ \mu\text{m}$ is the baseline for limb pointing. This has worked in the past to well within our requirements (for example in CIRRIS-1A) and is proposed for future space-borne experiments, such as the HIRDLS instrument on Eos.

Straw man instrument package With proper choices from the above suggestions we can make *definitive measurements of all necessary components of the major cooling processes in the thermosphere, and thus determine if they are modeled correctly* for the rather extensive range of conditions that the tether experiment can probe. The instrument module which contains the spectrometer would measure from approximately 90 km up to the module height. It would include spectroscopic measurements of (1) the $15\ \mu\text{m}$ CO_2 bands, for atmospheric cooling and pointing; (2) the $5.3\ \mu\text{m}$ NO and $4.3\ \mu\text{m}$ CO_2 bands; and (3) the $63\ \mu\text{m}$ atomic fine structure line ($J = 1 \rightarrow 2$) of O^3P . Neutral mass spectrometer measurements must include oxygen atoms (mass 16), NO (mass 30), and CO_2 (mass 44).

It is amply demonstrated from SPIRE³ and CIRRUS-1A⁴ measurements, SAO measurements of O^3P ,⁸ and ISO characteristics⁹ that the proposed measurements are possible given sufficient payload resources. Appropriate detector manufacturers and users are currently being contacted in order to investigate the available performance vs. cooling. This will allow a tradeoff study of size, weight, complexity, etc. to be made on the spectrometer portion of the payload.

Combining limb and *in situ* measurements The proposed tethered satellite experiment combines *in situ* measurements of neutral composition with limb measurements of atmospheric emissions. In order to combine such data in a meaningful way, the geometry of the limb measurements must be such that the measurements are essentially local. Figure 1 shows weighting functions for measurement of emission from the $63\ \mu\text{m}$ line of O^3P calculated for various tangent heights from a platform at 200 km altitude. O atom concentrations are taken from the MSIS-86 thermospheric model under conditions of low solar activity.¹⁰ It is apparent from the figure that the sampling in the limb geometry is very strongly peaked near the tangent height, providing measurements that are essentially local in nature. The horizontal smearing from the tangent geometry corresponds to several tens of seconds of *in situ* observing at the orbital velocity of $7.8\ \text{km s}^{-1}$.

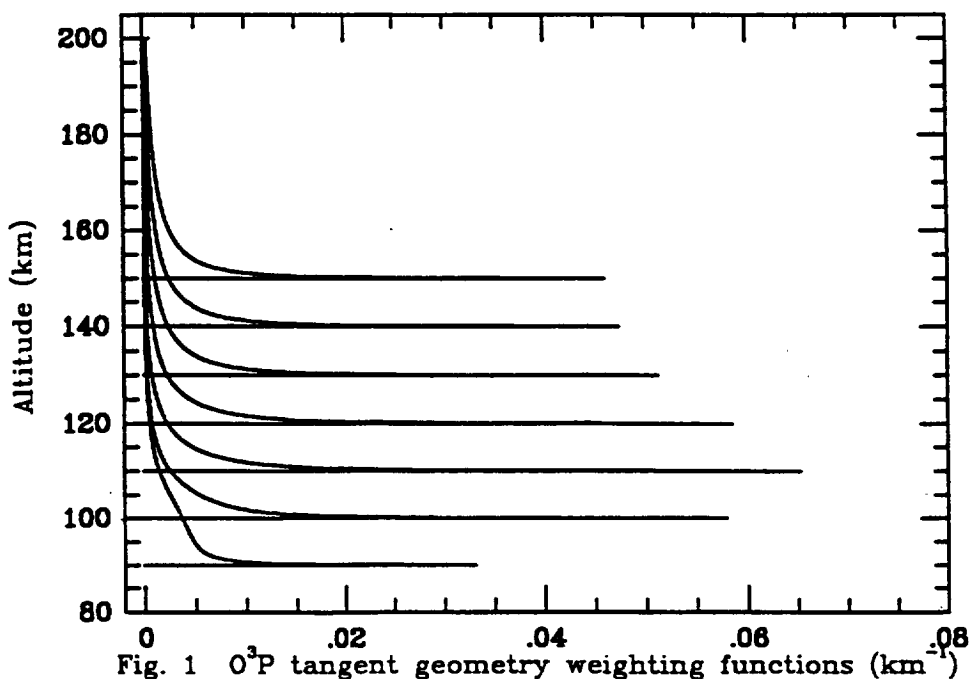
CONCLUSIONS

The concept for a tethered aeronomy mission described in this paper and two other Center for Astrophysics papers in these proceedings^{1,2} is one wherein an experiment requiring modest resources and using mature technology can produce unique scientific results. These results are of particular interest because of their importance to the issues of global warming and stratospheric ozone photochemistry.

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Paper ThFUTA-6

TETHERED MULTI-PROBE FOR THERMOSPHERIC RESEARCH

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TETHERED MULTI-PROBE FOR THERMOSPHERIC RESEARCH

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Abstract

This paper focuses on the dynamics, on-board instrumentation, and science that can be conducted by means of a multi-probe tethered system deployed into the Earth's lower thermosphere. Particular attention is given to the measurement of cooling processes in the lower thermosphere. According to a number of authors, thermospheric cooling may result from an increased concentration of CO_2 and CH_4 in the atmosphere and, hence, is related to global warming of the troposphere. Since a key issue of low-altitude tethered systems (with one or more probes) is the propellant consumption required for orbital maintenance, simple formulas are derived to estimate the propellant consumption per orbit. The dynamics and thermal requirements of a dual probe system deployed, from a low-eccentricity orbit, into the lower thermosphere is, then, investigated in order to prove the feasibility of such mission with present day tether technology.

Introduction

Tethered satellites provide a tool for exploring the lower portion of the Earth's thermosphere extending above 90 km of altitude. By means of a tethered system, a probe or a number of vertically spaced probes can be deployed into the relatively dense atmosphere for taking simultaneous, *in-situ* measurements of vertical profiles and spatial gradients of atmospheric quantities in the region of interest.

At a time of increased public concern over the Earth's environment and its future trends, measurements in the lower thermosphere of the predicted effects of increased concentrations of "greenhouse gases" is of great current interest. It is postulated by a number of scientists [1-3], utilizing General Circulation models, that the increased greenhouse gases released into the atmosphere will lead to a global warming of the troposphere (0-10 km) and a stronger global cooling of the mesosphere (50-80 km) and lower thermosphere (above 90 km). The average temperature in the troposphere is estimated to *increase* by 1-5 K in the next century. The temperature effects in the lower thermosphere, according to some authors [1, 2], are amplified with respect to similar effects in the mesosphere [4, 5] with an average *decrease* in temperature of the lower thermosphere predicted to reach 40 K by the mid of the next century. The temperature changes, moreover, would involve changes in the *vertical profiles* of minor atmospheric species like NO, O, O_3 , H_2O , OH, HO_2 , CO, H in the stratosphere, mesosphere, and lower thermosphere [6, 7]. Computer modeling of global circulation predict relatively steep vertical gradients, especially in the altitude band 100-125 km, of the neutral temperature redistribution and also of the rearranged concentrations of atomic Oxygen and Nitrogen with respect to present day conditions (see Fig. 1 reprinted, with authors' permission, from Ref. [1]). It is also interesting to point out that the vertical temperature redistribution is more influenced by the solar cycle than the latitude-longitude distribution on a constant-pressure surface [1], thereby indicating the importance of taking point and gradient measurements at the above-mentioned altitudes.

A multi-probe tethered system lowered into this region of the atmosphere could measure the horizontal (along a spherical shell) and vertical distributions of minor species concentrations and spectroscopic emissions characteristic of the primary coolant species in these regions. The data so obtained would allow one to develop a more complete and detailed picture of the relevant cooling processes in the upper atmosphere.

TIGCM NEUTRAL TEMPERATURE (DEG K)

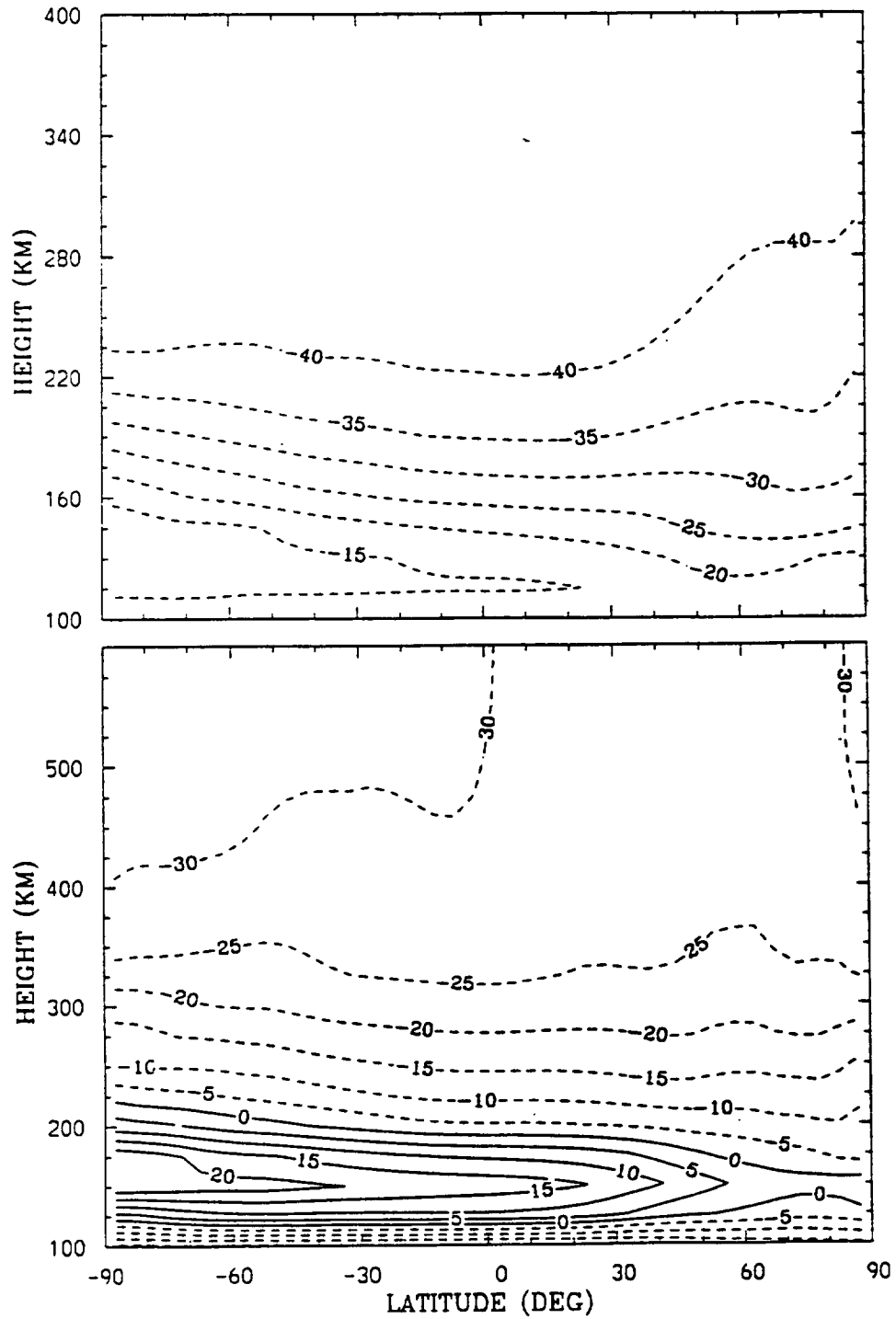


Fig. 1. Contours in height and latitude of the zonally averaged field ("doubled CO_2/CH_4 " - "present conditions" of temperature, ΔT , December solstice at 00 UT. (a) Above: solar minimum (b) Below: solar maximum [Graphs and caption reprinted with authors' permission from Ref. 1].

Tethered System Dynamics at Low Altitudes

A probe or a number of probes attached along a long tether can be deployed from a mother platform (e.g., the Space Shuttle) into the relatively dense low thermosphere. Several papers and a book (Ref. [8-10] just to mention a few) address the dynamics and stability of single-probe atmospheric tethered systems at low altitudes. Also, the study of several aspects of the dynamics of multi-probe tethered systems has been more recently undertaken by some authors [11, 12]. Only a few key issues, related to multi-probe systems flying at low altitudes, will be addressed in this paper.

It should be pointed out that tethers, on the one hand, do allow the deployment of probes into the relatively dense atmosphere while keeping a large mother platform, like the Shuttle for example, outside of the high drag region. On the other hand, tethers of present day technology have substantial drag areas.

After approximating locally the atmospheric density with an exponential function with reference density and scale height at the bottom tip of the tether and integrating the drag effect over the tether length, the total drag on the tether is readily obtained as follows:

$$D_{tet} = -\frac{1}{2} C_D \bar{\rho} \bar{v}^2 A_T^{eq} \quad (1)$$

where the equivalent drag-force area of a cylindrical tether is [13]

$$A_T^{eq} = \bar{H}_s d [1 - \exp(-L \cos(\theta)/H_s)] \quad (2)$$

In the equations above, \bar{H}_s is the atmospheric scale height, $\bar{\rho}$ the atmospheric density, and \bar{v} the wind velocity (all the barred quantities are computed at the bottom tip of the tether), L and d are the tether length and diameter, respectively, C_D the drag coefficient, and θ the angle between the tether and the local vertical (LV), which is frequently called the in-plane libration angle. The equations above reduce the tether drag-force contribution to an equivalent drag-force area to be added to the probe at the tether's end.

Figure 2 shows the effective drag-force area per unit diameter (in mm) for a vertical and cylindrical tether vs the altitude of the bottom tip for $L = 60$ km and $L = 80$ km and for average atmospheric conditions. A typical diameter of a high-stress, long atmospheric tether is about 0.5 mm and, consequently, the tether contribution to the overall drag force is usually comparable or larger than the contribution of the probe (or probes) attached to it.

A large drag area implies a large propellant consumption for orbital maintenance. After assuming that the tethered system is on an elliptical orbit with small eccentricity e , the impulse per orbit per unit drag area A can be computed as follows [14]:

$$I_{A,rev} = 2\pi\sqrt{\mu a} C_D K [I_0(b) + 2eI_1(b)] \quad (3.1)$$

where

$$K = \rho_p \exp(-b) \left(1 - 2\Omega_E \cos i / \sqrt{\mu / \alpha^3} \right) \quad (3.2)$$

$$b = ae / H_s \quad (3.3)$$

The symbols in eqns. (3) are as follows: μ and Ω_E the Earth's gravitational constant and rotational rate, respectively; a and e the orbit semi-major axis and eccentricity; C_D the drag coefficient; I_0 and I_1 the modified Bessel functions of order zero and one; ρ_p and H_s the atmospheric density and scale height measured at the perigee of the lowest point in the tethered system.

Consequently, the propellant consumption per orbit per unit drag area is simply:

$$P_{A,rev} = I_{A,rev} / g I_{sp} \quad (4)$$

where I_{sp} is the specific impulse and g the Earth's gravity acceleration.

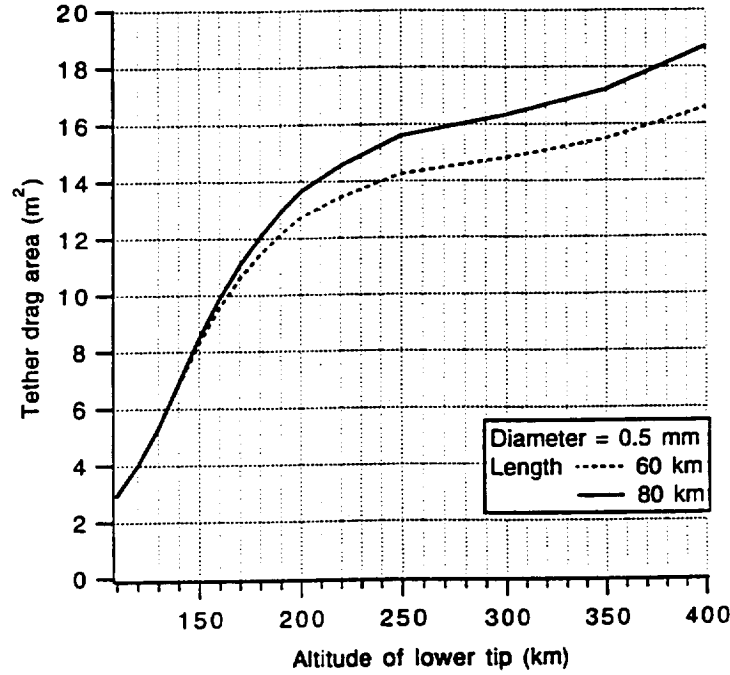


Fig. 2. Equivalent drag-force area per unit diameter (in mm) of two vertical and cylindrical tethers vs altitude of the bottom tip for average atmospheric conditions.

Figure 3 shows $P_{A,rev}$ vs the apogee altitude of the bottom tip (or the bottom probe) of a tethered system with a 110 km or a 120 km perigee and a specific impulse of 250 s (an average value for Hydrazine systems). The drag area A mentioned above is the total drag area, i.e., the sum of the equivalent drag-force area of the tether and the overall drag area of the probes. The contribution of additional probes along the tether can be readily computed by scaling the drag area of the higher probes (subscript i , $i = 2, \dots, n$ where n is the total number of the probes) by the atmospheric density at the tether lowest probe (subscript 1), i.e.,

$$A_i^{eq} = A_1 \rho_i / \rho_1 \quad i = 2, \dots, n \quad (5)$$

For example, a system in a *circular orbit* with an 80-km-long, 0.5-mm-diameter tether with two probes of 1-m^2 each, separated by one scale height (~ 8 km in this case), and the lowest probe at 120 km of altitude, would have a total drag area $A = 5.37 \text{ m}^2$ and require ~ 16 kg/orbit (or 260 kg/day) of Hydrazine for orbital maintenance. The same propellant consumption is required for an *elliptical orbit* of $110\text{km} \times 160\text{km}$ (measured at the bottom probe) while for a 110-km *circular orbit* (at the probe) the propellant consumption would be a staggering 68 kg/orbit (or 1105 kg/day). Elliptical orbits appear to

be mandatory, with present day tether technology, for a reasonable mission duration and a perigee altitude of the lowest probe of 110 km.

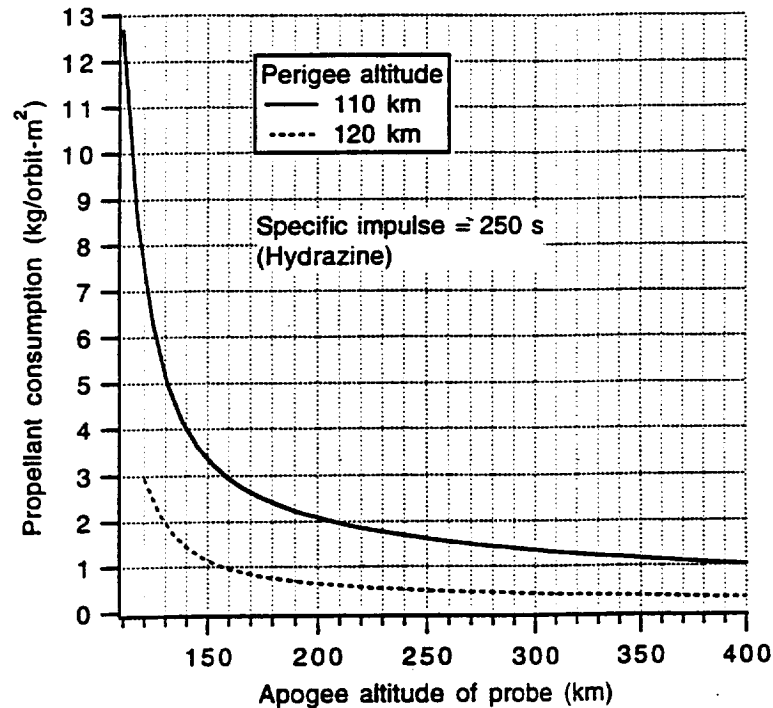


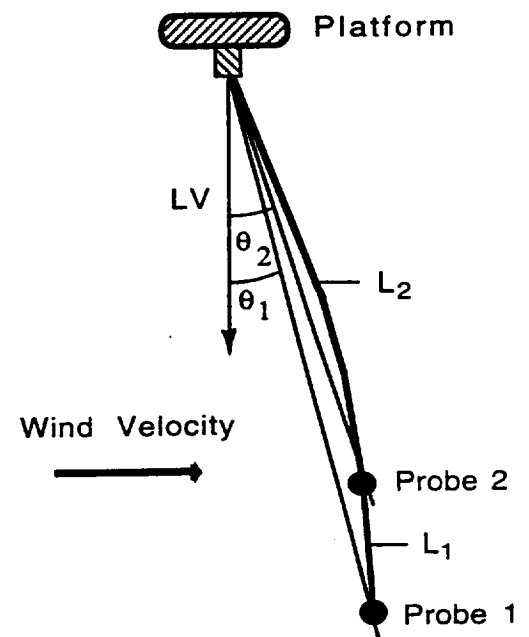
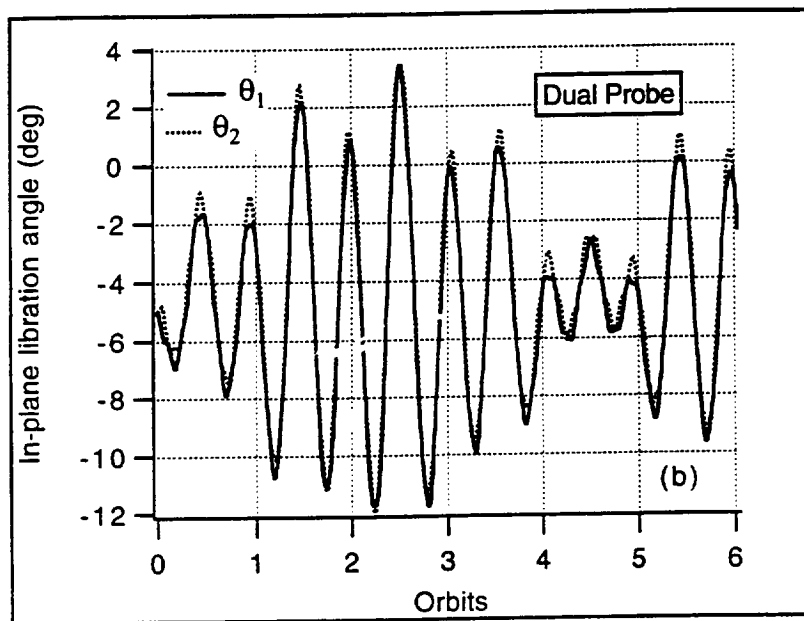
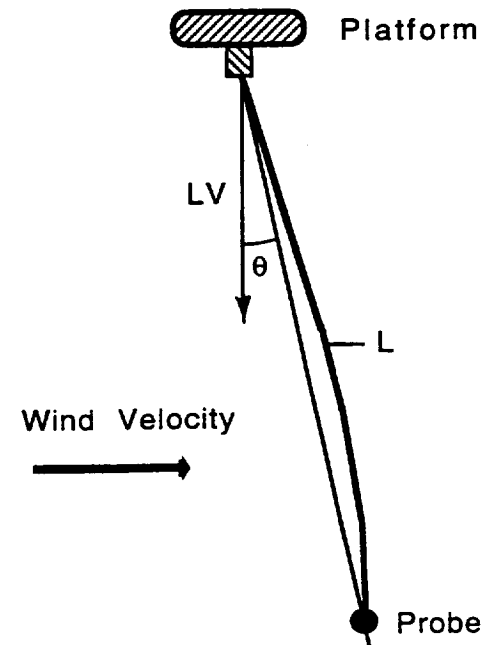
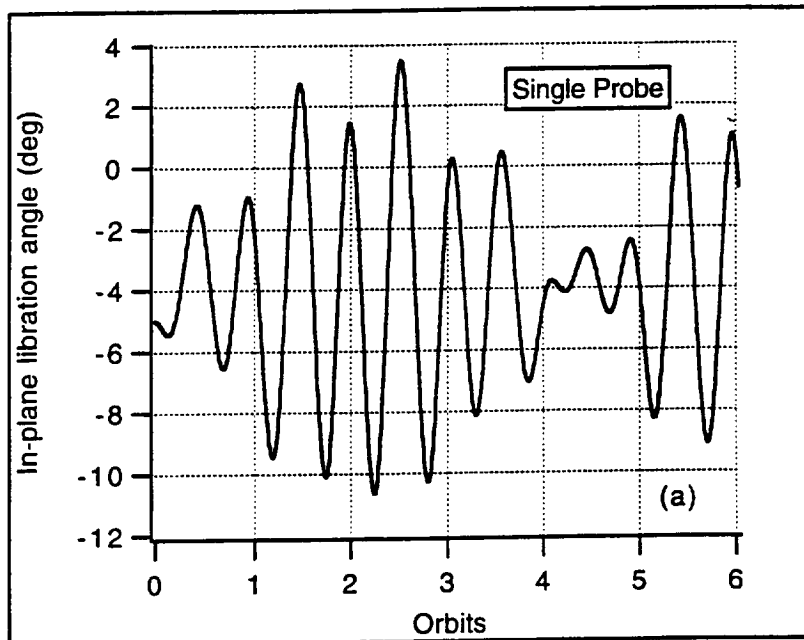
Fig. 3. Propellant consumption per orbit per unit drag area vs apogee altitudes of the bottom tip (or the lowest probe) for tethered systems with 110 km and 120 km perigee and a specific impulse of 250 s.

Since the in-plane libration frequency is independent of the mass distribution along the tether, the libratory modes of a multi-probe tethered system have the same frequency as the librations of a single-probe tethered system. Differences in dynamic response between the two arise from the differing lateral modes of the tether which, on the contrary, depend on the mass distribution. We refer to the modes above as *lateral modes* because even if, strictly speaking, any mode involves all the degrees of freedom, in the present case the eigenvectors of specific modes affect only certain degrees of freedom. For a comprehensive treatment of eigenvalues and eigenvectors of multi-body tethered systems see Ref. [12].

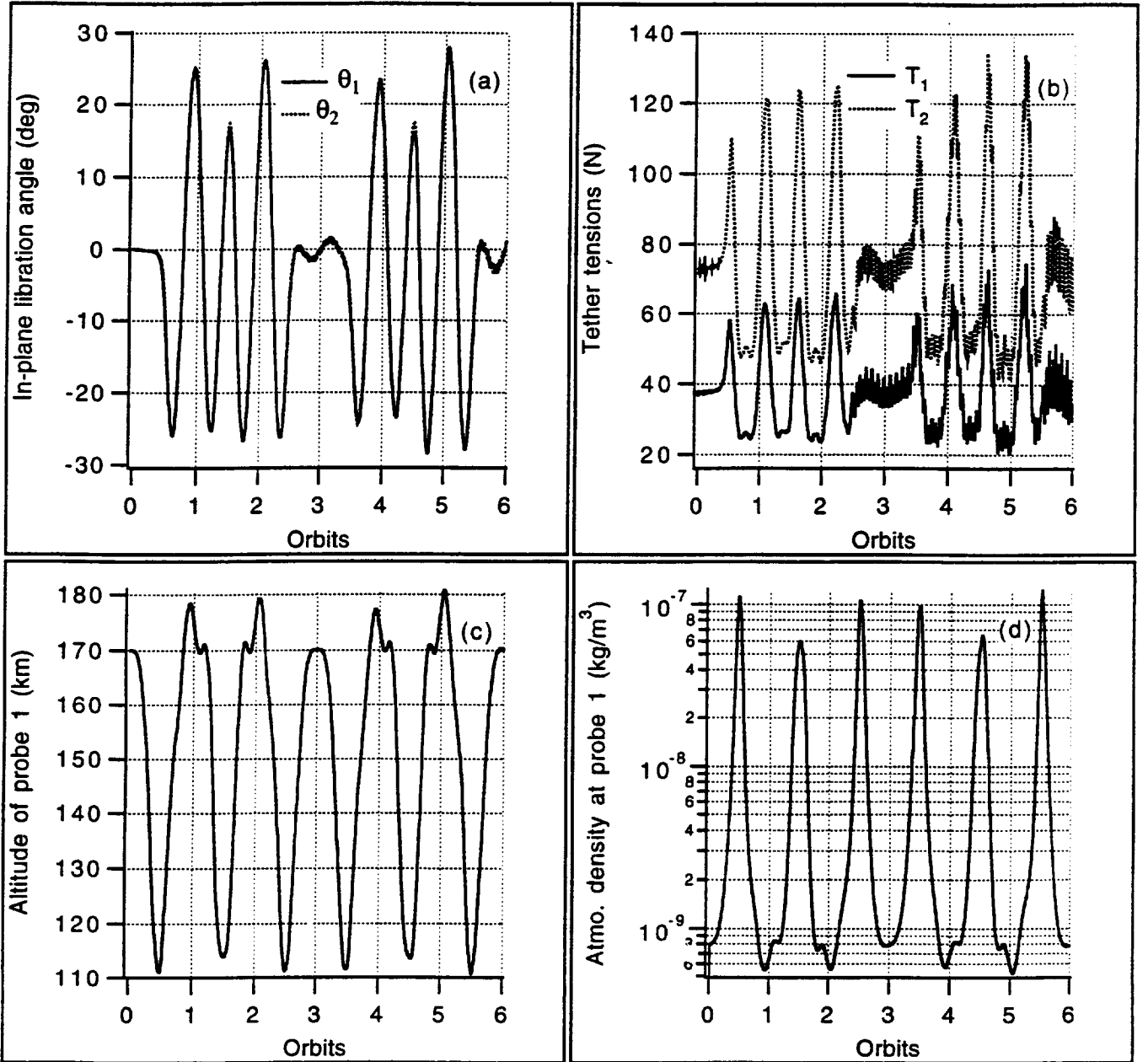
In order to exemplify the statements above, the dynamics of a single-probe and a dual-probe system are compared in Figs. 4(a) and 4(b) for the following numerical values: upper platform orbit of 200kmx200km; $L = 80$ km for the single-probe system; $L_1 = 72$ km and $L_2 = 8$ km (i.e., one atmospheric scale height) for the dual-probe system ($L = L_1 + L_2 = 80$ km); tether diameter = 0.5 mm; probe 1 mass = probe 2 mass = 100 kg; probe 1 frontal area = probe 2 frontal area = 1 m²; and orbital inclination = 28.5°. The simulations were carried out with a lumped-mass computer model for tethered systems [11] with an oblate Earth, a non-spherical gravity field, and a Jacchia 77 atmospheric density model. Since the orbit of the mother platform is circular, the in-plane librations are primarily forced by the atmospheric density variations along the orbit associated with the Earth's oblateness and the diurnal bulge.

Figures 5(a)-5(d) show the dynamics of an hypothetical dual-probe system that could accomplish the scientific goals described in the Introduction of this paper. Since an extended orbital coverage at the altitude band of interest is required for global measurements of atmospheric characteristics, an

orbital inclination of 57° , which is the maximum allowed to the Shuttle, has been adopted. Also, a relatively small eccentricity is desirable in order to scan large portions of the Earth's atmosphere near the perigee height. Numerical values of the system parameters are, therefore, as follows: upper platform on a $200\text{km} \times 250\text{km}$ orbit; tether diameter = 0.5 mm ; $L_1 = 85\text{ km}$ and $L_2 = 5\text{ km}$ (L = overall length = 90 km); probe 1 mass = probe 2 mass = 100 kg .



Figs. 4. In-plane librations of two 80-km-long tethered systems with an upper platform on a 200-km circular orbit and an overall tether lengths of 80 km (see text): (a) single-probe system; and (b) dual-probe system.



Figs. 5. Dynamic response of a tethered system with two probes separated by 5 km, an upper platform in a 200kmx250km orbit and an overall tether length of 90 km: (a) in-plane libration angles (θ_1 lower probe, θ_2 higher probe); (b) tether tensions (T_1 lower tether segment, T_2 higher tether segment); (c) altitude of lower probe; and (d) atmospheric density at lower probe.

With an elliptical orbit, the amplitudes of in-plane oscillations increase because of the larger altitude variation over one orbit which results in a stronger (than for a circular and inclined orbit) pumping of these oscillations. Masses of the probes can be increased substantially with respect to the values adopted here with no major impact on the system dynamics but with an increase of the propellant consumption due to the required increase of tether diameter. The dynamics of the dual-probe system with a perigee at 110 km of altitude is stable and the most severe system requirement is

the propellant consumption for orbital maintenance. Thanks to the dual probe configuration, the maximum tension in the lower tether segment (T_1) is about half the tension in the upper tether segment (T_2). Consequently, the diameter of the lower tether segment, which is responsible for a large portion of the drag on the system, can be smaller than the diameter of the upper tether segment, thus reducing the propellant consumption with respect to an equal-diameter-tethers configuration. The tether diameters of the dual-probe system in this paper are 0.3 mm and 0.5 mm (consistent with a safety factor of 4) for the lower and upper tether segments, respectively. The propellant consumption for orbital maintenance for this system is estimated to be about 11 kg/orbit (or equivalently 178 kg/day) of Hydrazine. A several-day-long mission could be handled by the Space Shuttle as a mother platform. Deployment of a low-altitude atmospheric system is also possible from a platform other than the Space Shuttle but mission duration and perigee altitude must be traded off for the propellant available on board. The lifetime without orbital reboosting of a typical low-altitude tethered mission with a perigee of 110 km and low eccentricity will be shorter than one orbit for an hypothetical platform mass of about 2000 kg.

Tether temperature is another concern for low-altitude atmospheric missions. Since the tether is in free molecular flow (at altitudes > 100 km) while the probes are in transitional flow, the tether is exposed to a higher heat flux than the probes. Furthermore, thermal shields can be added to the probes but are not applicable to long, thin tethers. Figure 6 shows the steady state temperature of a tether vs altitude in sunlit and eclipse conditions. In deriving these temperature values, the thermal conduction along the tether itself has been neglected and average values of emissivity and absorptivity have been adopted. Steady-state temperatures at 120 km of altitude can be handled by conventional tether materials like stainless steel while for the temperatures at 110 km, more advanced tether materials like coated boron fibers, graphite HS, or tungsten should be considered [15]. It should also be pointed out that only the last portion of the tether (with a typical length of one scale height) is subjected to demanding thermal conditions. This last portion must be thin (and, consequently, highly stressed) for reducing the drag area, and thermally resistant for withstanding the high temperatures encountered. The rest of the tether has more relaxed thermal and stress requirements.

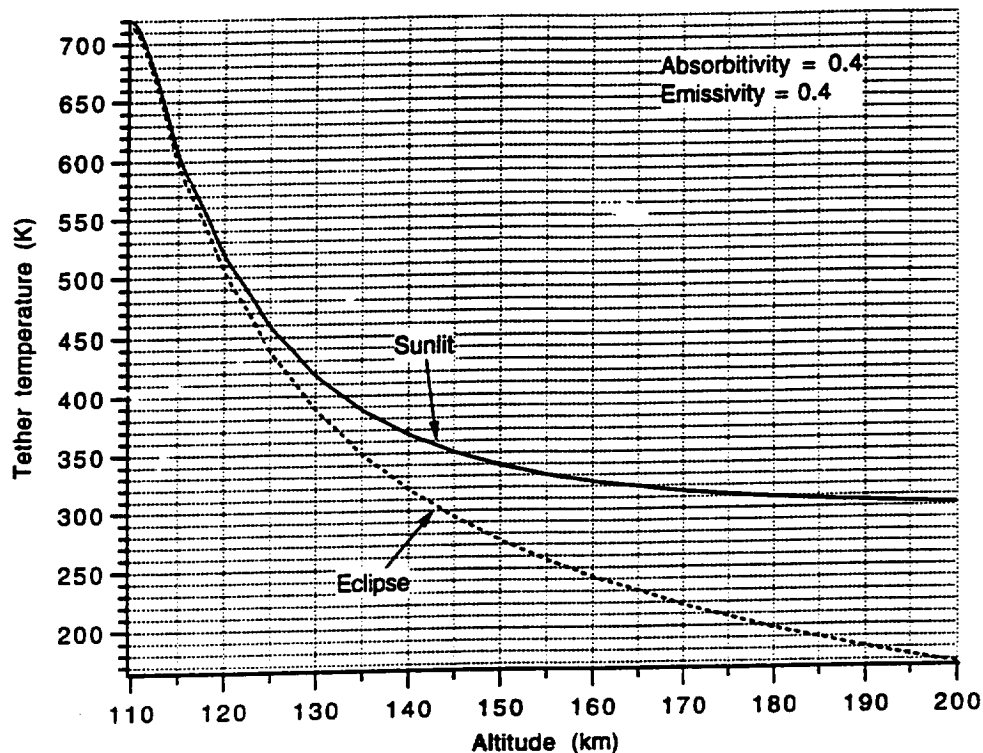


Fig. 6. Steady-state temperature of tether vs altitude.

On-board Instrumentation

In the following we describe briefly the core instrumentation needed for the measurement of thermospheric cooling processes. The Smithsonian Astrophysical Observatory-supplied portion of the atmospheric measurement packages [16] would include an array detector-based limb sounding spectrometer which would measure the 15 micron CO₂ bands and the 5.3 micron NO and 4.3 micron CO₂ bands. Additionally, we hope to be able to include a far infrared Fabry-Perot instrument for measuring the 63 micron atomic fine structure line ($J = 2 \leftarrow 1$) of O³P.

Detailed measurement of the 15 micron CO₂ bands provides a primary measurement of atmospheric cooling. Below about 120 km, infrared emission by CO₂, which has been excited by collision with oxygen atoms, is the dominant cooling mechanism in the thermosphere. An additional 15 micron channel will measure lower altitude CO₂ for pointing of the limb spectrometers. The 5.3 micron NO measurements include both the fundamental band of NO and vibrational hot bands, determining details of the formation of NO from O₂ and hot nitrogen atoms. Cooling by emission from the NO fundamental band is the major source of atmospheric cooling from about 120-200 km. Above about 200 km, cooling by the 63 micron emission from the fine structure transition in atomic oxygen dominates the atmospheric cooling. When complemented by mass spectrometric measurements, these emission measurements will provide definitive data on the major cooling processes in the thermosphere.

Additional instrumentation on board the probes could include GPS receivers for accurate position determination and accelerometers and tether-attachment tensiometers for measuring drag-induced dynamical perturbations and atmospheric density.

Conclusions

Limb observations of characteristic spectroscopic emissions as well as in-situ measurements of the concentrations of trace constituents which perform the primary cooling in the thermosphere and ionosphere can be carried out by means of a multi-probe tethered system deployed into the Earth's lower thermosphere. These measurements are of particular importance in exploring the effect of the build-up of CO₂ on the temperature structure of the upper atmosphere. A multi-probe tethered system is uniquely suitable for reaching the required low altitudes and taking simultaneous vertically-spaced measurements with a global coverage of the Earth at the altitudes of interest. A perigee altitude as low as 110 km, for the lowest probe, can be maintained for several days with a small-eccentricity orbit and a system deployed from a platform with a substantial propellant supply (e.g., the Space Shuttle). Alternatively, a circular orbit of 120 km, for the lowest probe, could be sustained for an equivalent duration and propellant consumption. Tether temperature and dynamic stability requirements for this system can be met with presently available tether materials and tested tether control technology. Future improvements in tether materials could further improve the present scenario.

Acknowledgments

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3.0 Analysis of SEDS-II Satellite Flight Data

A paper, presented at the *Fourth International Conference on Tethers in Space*, is included in the following to illustrate the results of the analysis of the acceleration levels and dynamic noise on-board the SEDS-II end-mass.

Paper WSEDSP-5

ACCELERATION LEVELS AND DYNAMIC NOISE ON SEDS END-MASS

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**Fourth International Conference on
Tethers in Space**

Sponsored by National Aeronautics and Space Administration,
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Smithsonian Institution, Washington, DC, 10-14 April 1995

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ABSTRACT

Spaceborne tethers offer a unique transportation capability for instrumented probes attached to orbiting platforms (e.g. Space Station) or access to otherwise inaccessible flight regions (e.g. Lower Thermosphere).

SEDS flights have provided the scientific community with a wealth of data. In this paper the authors focus their attention on the acceleration levels on board the tethered end-mass and how they are affected by the tether motions and environmental perturbations. The absence of any damping device gives a realistic picture of a typical "tethered environment" as well as pinpoint its limits or suggest necessary modifications.

Simplified models have been developed in order to understand the features observed in the acceleration spectra. A good agreement has been found between the observations and the theory.

INTRODUCTION

The successful flights of the Small Expendable Deployer System (SEDS) have demonstrated the capability of tethers in space transportation. Long tethers can trawl deep into the Earth's lower atmosphere to perform continuous "in-situ" measurements of chemical species² and remote sensing of the Earth's gravity gradient^{6,8}. Moreover, space tethers might of insulate experiments from a "noisy" (e.g. high dynamic activity) and/or contaminated environment^{9,11} when a "quiet" acceleration envelope is needed.

In this paper we concentrate on the spectral contents of the accelerations on board SEDS-2 and estimate the dynamic noise. We have approached the problem by separating the various contributions to the acceleration levels in three groups, namely the tether, the platforms' dynamics and the environmental perturbations.

THE "TETHER" ENVIRONMENT

Let us consider the two-dimensional equations of motion for a dumbbell system orbiting the earth at a constant rate Ω under the hypotheses of small librations and massless tether

$$\begin{aligned} \ddot{\vartheta} + 2\frac{\dot{l}}{l}(\dot{\vartheta} - \Omega) + 3\Omega^2 \frac{\sin 2\vartheta}{2} &= \frac{T_D}{ml} \\ \ddot{l} - l(\dot{\vartheta} - \Omega)^2 - l\Omega^2(3\cos^2 \vartheta - 1) &= \frac{(D - T)}{m} \end{aligned} \tag{1}$$

where:

ϑ = angle between line connecting end masses and local vertical (i.e. in-plane angle)
 l = tether length
 T = tether tension
 D = perturbing acceleration
 TD = generalized perturbing torque
 m = equivalent mass

In the absence of perturbations, the specific forces measured onboard a tethered platform are $-T$ along the tether and zero in the perpendicular direction. Namely, the axis along the libration is in "free-fall", while the other is affected by a "bias" term. Consequently the knowledge of the tether direction with respect to the end-mass is necessary in order to make acceleration measurements onboard a tethered satellite. Furthermore, the influence of the tether must be carefully characterized as a perturbation in order to discriminate it from the other accelerations.

Tethers have a wide spectrum of oscillations. Under the hypotheses of small angles, the in-plane and out-of-plane libration frequencies are $\sqrt{3}\Omega$ and 2Ω , respectively. The lateral (i.e. "string") and longitudinal oscillations frequencies $\omega_n/2\pi$ can be computed by solving the equation:

$$\begin{aligned}
 z_n \tan z_n &= \frac{\mu l}{M} \\
 z_n &= l \omega_n \sqrt{\frac{\mu}{Y}}
 \end{aligned} \tag{2}$$

where:

μ = tether linear density

l = tether length

M = equivalent mass

$Y = EA$ for longitudinal modes = product between the tether Young's modulus and the cross section area
 or

= T for lateral modes = tether tension (assumed constant along tether)

The spring-mass frequency of the two body system connected by a massless tether is

$$f = \frac{1}{2\pi} \sqrt{\frac{EA}{lM}} \tag{3}$$

As we shall discuss later on, there are various sources of external perturbation that can deposit energy in these modes. Tethers can naturally abate only perturbations acting along the longitudinal direction through structural damping. All other modes, once excited, cannot be damped naturally unless specific control strategies are applied ^{4,9}.

SEDS-2 FLIGHT

Both SEDS flights were equipped with a 3-axis accelerometer. The data were analyzed in order to estimate the natural acceleration environment of a tethered platform, without any stabilization device.

Figure 1 shows a schematic of the end-mass with the body reference frame and the location of the instruments ¹⁰. The end-mass properties are given in Table 1 and the characteristics of the accelerometers are given in Table 2.

Table 1. SEDS-2 End-Mass Characteristics	
Mass (kg)	25.9
Moments of Inertia (kg-m ²)	X) 0.285; Y) 0.464; Z) 0.545
Accel. X Location wrt CM (m)	X)-1.90 × 10 ⁻³ ; Y)-1.84 × 10 ⁻² ; Z)-8.1 × 10 ⁻³
Accel. Y "	X)-1.84 × 10 ⁻² ; Y) 1.68 × 10 ⁻³ ; Z) 2.85 × 10 ⁻²
Accel. Z "	X) 1.82 × 10 ⁻² ; Y) 1.97 × 10 ⁻² ; Z) 6.88 × 10 ⁻³
Tether Attachment Point Location wrt CM (m)	X) 0.165; Y) 0.184; Z) -8.86 × 10 ⁻³

Table 2. Accelerometer Characteristics	
Type	Sundstrand QA 2000-030
Range	1) 1 mg; 2) 5 mg; 3) 50 mg
Resolution	1) 8 μg 2) 40 μg; 3) 400 μg
Sampling Rate	8 Hz

SEDS second flight provided about 8 hours of data during station keeping before the onboard battery exhausted its energy. The following analysis will focus on this set of data because of the stationarity of this phase.

In both flights, the analysis of the magnetometer data showed that the end-mass spun around the tether axis ¹. In the second flight the spin rate increased until it reached 35 °/s (≈ 6 rpm) at about 26000 seconds, as shown in figure 2. Note that the time is counted from the ejection of the end-mass from the Delta II stage. The end of the deployment was reached at about 6600 seconds.

The frequencies of SEDS-2 are given in Table 3 and the mass properties adopted are:

$$\mu = 3.3 \times 10^{-4} \text{ Kg/m}$$

$$l = 20 \text{ Km}$$

$$M = 26 \text{ Kg}$$

$$EA = 15,000 \text{ N}$$

$$\Omega = 1.14 \times 10^{-3} \text{ rad/s}$$

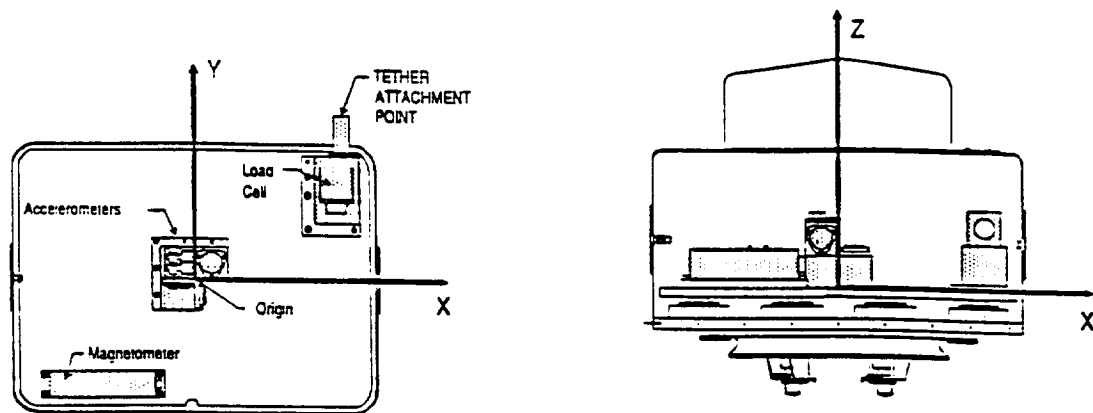


Figure 1. SEDS end-mass schematic

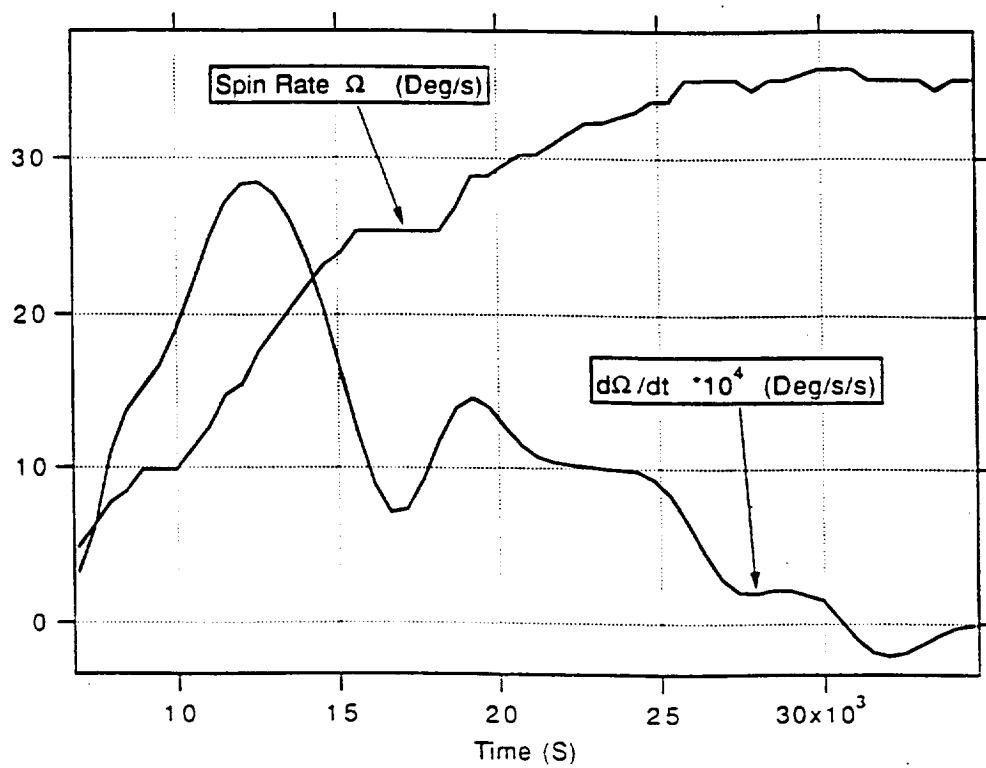


Figure 2. End-mass spin and spin rate during station keeping.

Table 3. SEDS-2 Natural Frequencies (Hz)	
In-plane libration	3.15×10^{-4}
Out-of-plane libration	3.64×10^{-4}
Spring mass	2.70×10^{-2}
Longitudinal Modes	
1st Mode	0.17
2nd Mode	0.34
3rd Mode	0.50
Lateral Modes	
1st Mode	1.91×10^{-3}
2nd Mode	3.82×10^{-3}
3rd Mode	5.72×10^{-3}

To compute the lateral frequencies we used the mean value of the tension provided by the load cells at the satellite attachment point (≈ 1.96 N). The tension acting on the end mass is shown in figure 3.

END-MASS RIGID BODY MOTION

In order to understand the dynamic coupling between tether and end-platforms we computed the attitude frequencies of the end-mass and the Delta's second stage.

As stated earlier the end-mass spun around the tether at increasing rate throughout the whole mission. Therefore, we erected a new body frame by aligning the new x axis ("yaw" axis) with the tether attachment point.

The new inertia matrix is:

$$\begin{vmatrix} 0.38 & 0.089 & 0.006 \\ 0.089 & 0.36 & -0.0032 \\ 0.006 & -0.0032 & 0.54 \end{vmatrix}$$

Rewriting the Euler's equations in the new reference frame and assuming that the rate around the x axis is constant and equal to the spin rate, under the hypotheses of small angular displacements around the other two axes, we obtain:

$$\begin{aligned} f_{\text{pitch}} &= 0.15 \text{ Hz} \\ f_{\text{roll}} &= 0.17 \text{ Hz} \end{aligned}$$

By comparing the end-mass attitude frequencies with SEDS-2 natural frequencies (Table 3) we notice that these frequencies are very similar to the longitudinal modes. A

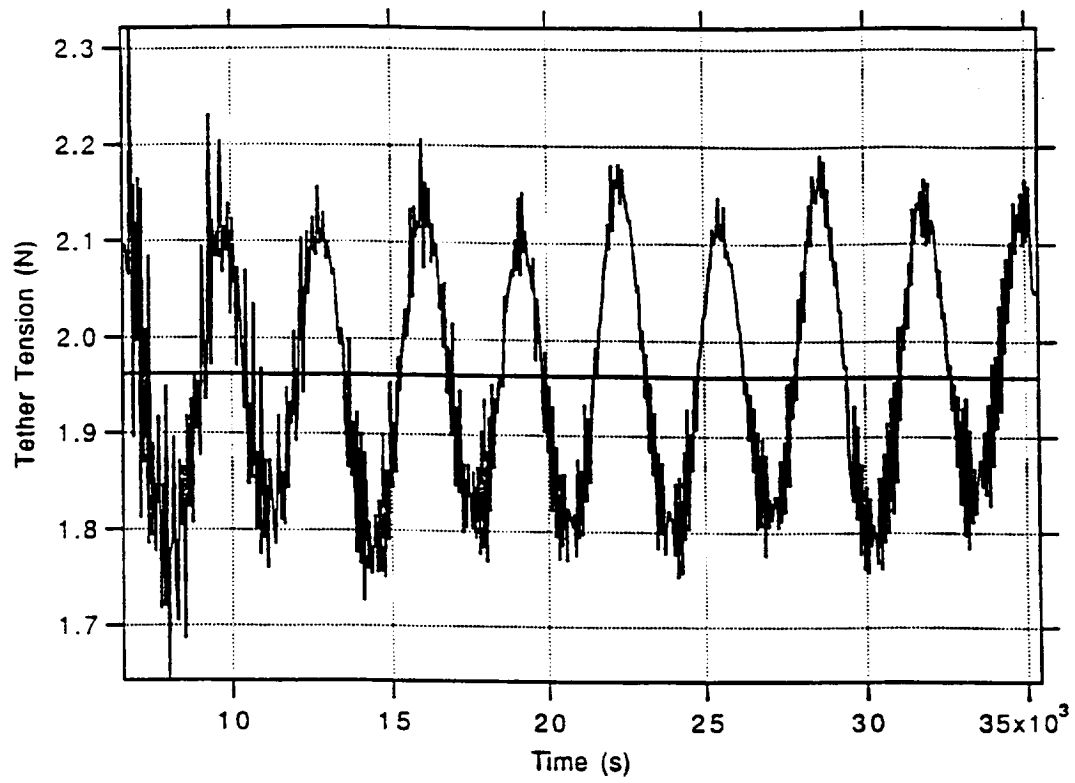


Figure 3. Tension modulus during station keeping

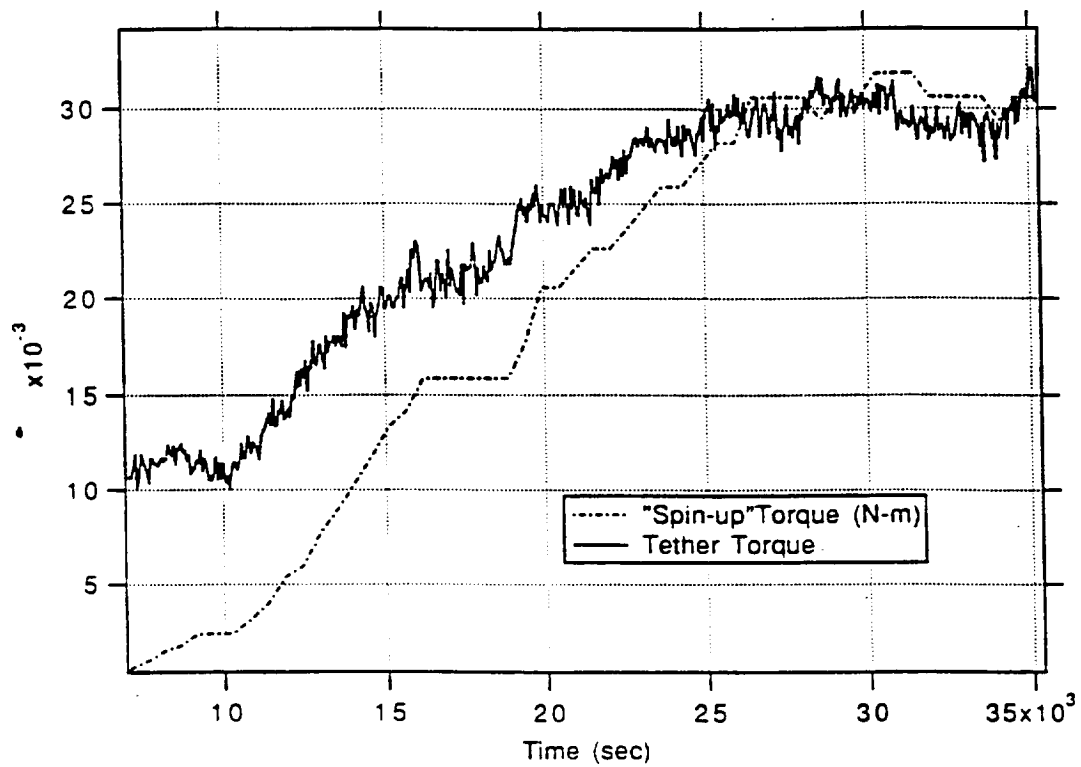


Figure 4. Comparison of tether torque and "spin-up" torque

resonance between tether modes and end-mass attitude frequencies could explain the increase in spin rate observed during the mission.

To this end we compared the modulus of the tether torque as measured by the load cells to the modulus of the torque necessary to "spin-up" the end mass obtained from the magnetometer data. By assuming that the end-mass is rotating only around the x axis ($\omega_x = \Omega$ and $\omega_y = \omega_z = 0$) we can rewrite the Euler equations as

$$\begin{aligned}M_x &\approx I_{xx} d\Omega/dt \\M_y &\approx -I_{xy} d\Omega/dt + I_{xz} \Omega^2 \\M_z &\approx -I_{xz} d\Omega/dt - I_{xy} \Omega^2\end{aligned}$$

where M_x , M_y and M_z are the torques required to spin-up the end mass. The comparison between the modulus of the "spin up" torque and the torque computed by the load cells data is shown in Figure 4. It can be noticed that, within the simplifications of our assumptions, the moduli are similar thus suggesting the torque required was mainly provided by the tether itself.

The Delta attitude frequencies were computed by adopting the inertia and geometric properties as reported in reference 5.

$$\begin{aligned}f_{pitch} &= 5.7 \times 10^{-3} \text{ Hz} \\f_{roll} &= 8.9 \times 10^{-3} \text{ Hz}\end{aligned}$$

ENVIRONMENTAL PERTURBATIONS

On the one hand, a thorough characterization of the environmental perturbations and their spectra is necessary in order to understand their influence on the system dynamics. On the other hand, SEDS flight instrumentation was intended only to assess the overall dynamic scenario. Consequently, this section will only briefly overview some of the external perturbation that may affect the acceleration environment onboard a tethered satellite.

The disturbances transmitted through the tether from the deployer to the satellite are not negligible. As already stated, only longitudinal perturbations can be naturally damped. The analysis of the damping mechanisms as well as their coupling to other modes are beyond the scope of this paper. As we shall see in the next section, the influence of the deployer motions on the acceleration levels of SEDS-2 end-mass is very significant.

Atmospheric drag is the main perturbation acting on satellites in LEO. For tethered satellites this influence is amplified because of their large exposed area. The mean atmospheric structure at a certain altitude is governed by factors like the type of heating processes taking place. At low thermospheric altitudes the mean atmospheric structure is dominated by semi-diurnal variations, as shown in figure 5 (from reference 7), with density variations of up to 30% in one orbit. Moreover, density variations due to transport processes can cause the mean density to vary up to one order of magnitude.

The observed density variations $\Delta\rho/\rho$ for some atmospheric processes are as follows ⁷:

Gravity Waves	5-20%
Tides	10-20%
Geomagnetic Storms	20-40%
Winds	20-30%

The occurrence of these phenomena and their frequencies vary with geomagnetic activity, altitude, latitude and local time ¹³ and it is hard to define a time scale for each variation.

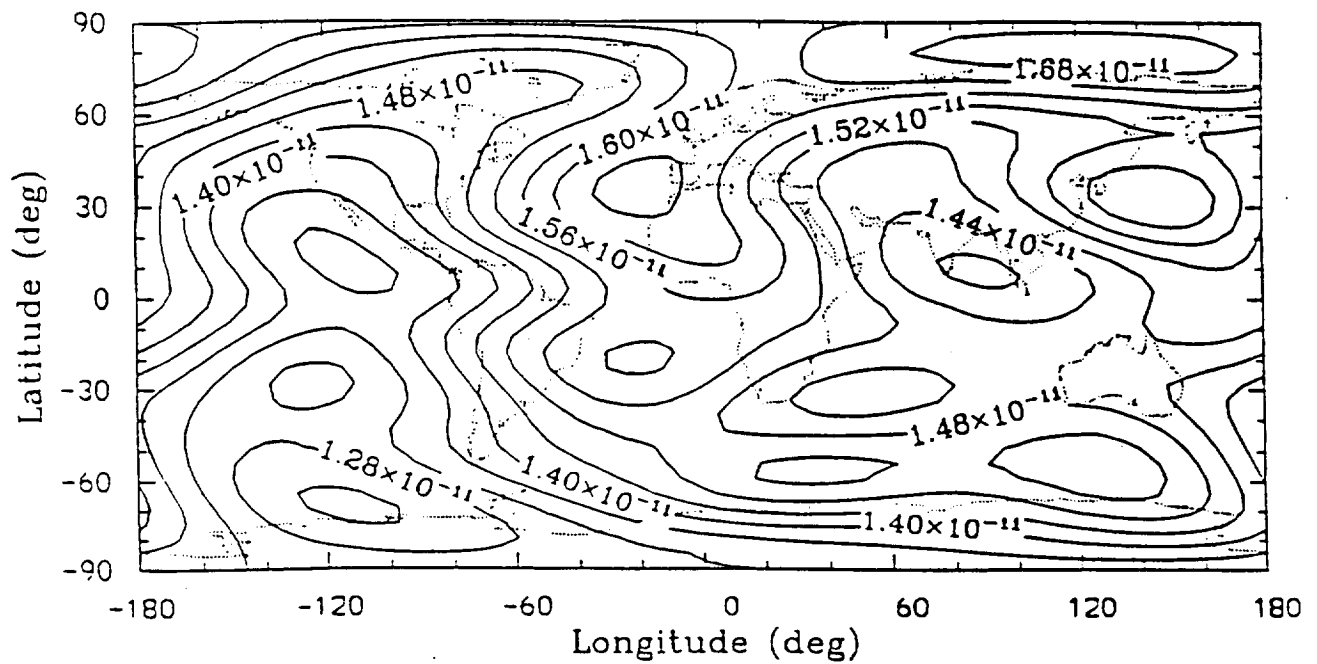


Figure 5. Modeled mean atmospheric density at 120 km altitude ($A_p=12$ and $F_{10.7}=180$ (from ref. 7))

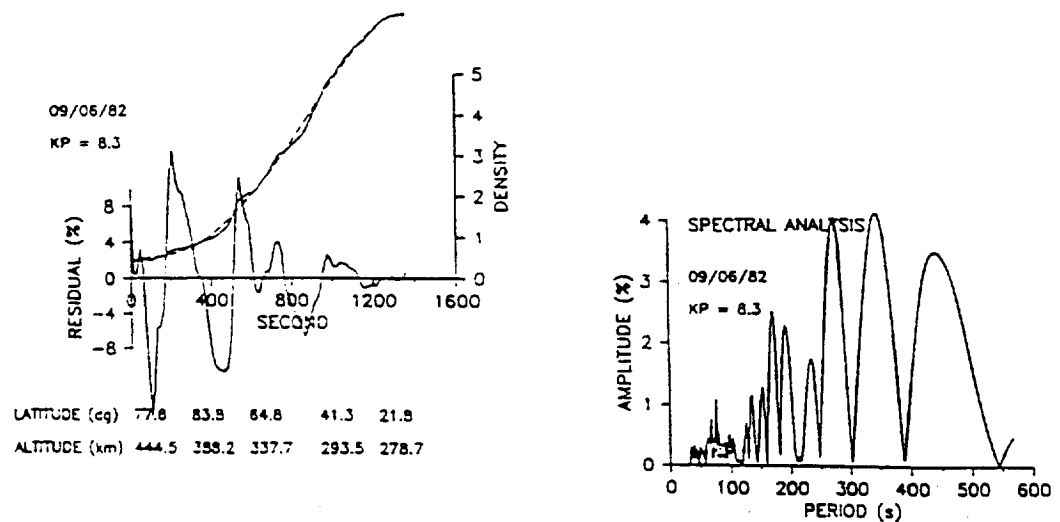


Figure 6. Fluctuations of total density for DE-2 measurements with respect to polynomial fitting and spectral analysis (from ref. 13)

Figure 6 depicts the fluctuations in total density experienced by the Dynamics Explorer-2 (DE-2) during a period of high solar activity. The spectral analysis shows that some atmospheric variations have periods similar to the lateral modes of tethered satellites (e.g. $\approx 10^2$ seconds). Most of these perturbations are going to act in a direction perpendicular to the tether line, therefore the lateral frequencies are going to be excited.

Thermal variations also play a major role causing the tether to expand and contract with a noticeable influence on the onboard accelerations levels. The main input in the tether thermal budget is the solar radiation. Variation in the total solar irradiance at various time scales are the subject of extensive studies. The variability on solar activity time scales (days or months), which are of interests for our missions, account to up 0.25% of the total irradiance (3.5 W/m^2). Variability at shorter time scales (minutes and hours), caused by solar oscillations do not appear to be very significant. "5-minutes" oscillations, for instance, are 3 ppm of the total irradiance signal. At present, our analysis of SEDS-2 data has not been able to detect any acceleration variation caused by thermal excursion.

FLIGHT DATA

In this paragraph we will present the results of the analysis of SEDS-2 accelerometers data. In our analysis we try to utilize our understanding of the tether dynamics and the influence of external perturbations in order to obtain an estimate of the acceleration environment onboard a tethered satellite.

We numerically computed the power spectra of the onboard accelerations by adopting the classical "periodogram" estimation¹². In order to keep the uncertainty of our estimates within a reasonable range we block-averaged the original data set at the expense of a reduced frequency resolution^{3,12}. Since the orientation of the end-mass is not accurately known¹, we chose to estimate the moduli of the accelerations. This choice is not going to give the lowest noise since the data will be altered by the rotational dynamics.

The first set of data were taken two, four and six orbits since ejection, respectively. The spectra are shown in figure 7a, 7b and 7c. The data were averaged at 0.25 seconds and we took 8192 data samples divided in two blocks. The range between 10^{-3} and 10^{-2} Hz shows two distinct peaks. The first peak is given by the system libration. Our analysis has shown that the tether final in-plane libration was ~ 4 deg. The second peak at 7.5×10^{-3} Hz is comparable to the Delta attitude frequencies. The discrepancy may be attributed to different values of the Delta's moments of inertia. Since the Delta's attitude was not controlled, the peak height is practically constant with time. In the 10^{-2} and 10^{-1} Hz range there is a peak of $0.9 \text{ m/s}^2/\sqrt{\text{Hz}}$ which is very close to the theoretical spring-mass frequency. As figure 7b and 7c show this peak decreases with time suggesting that the mode has been damped. Another explanation of these peaks could be given by the coupling between the Delta attitude and the tether lateral modes. As time progresses some peaks disappear or merge like the harmonic at 1.25×10^{-2} and 1.6×10^{-2} Hz. The power spectrum in the frequency range between 10^{-1} and 1 Hz decreases inversely with the frequency at the beginning of the station keeping and stabilizes at about $10^{-3} \text{ m/s}^2/\sqrt{\text{Hz}}$ after 6 orbits. The coupling between end-mass modes and tether modes plays the major role in this frequency range.

Figure 8 shows the spectra of the x and z acceleration components. The z axis was mostly perpendicular to the spin axis and this explains the lower noise at low frequencies. On the other hand, the end-mass attitude frequencies are now more discernible in the 0.1-2 Hz range. The dynamic noise in this range is practically the same for both axis. The spectra of the two acceleration components in the 10^{-3} - 10^{-1} Hz range, differ by an order of magnitude. By assuming that the end-mass and the delta attitudes were stabilized, like it would be the case in a scientific mission, we could extrapolate that the dynamic noise would tend to $5 \times 10^{-4} \text{ m/s}^2/\sqrt{\text{Hz}}$.

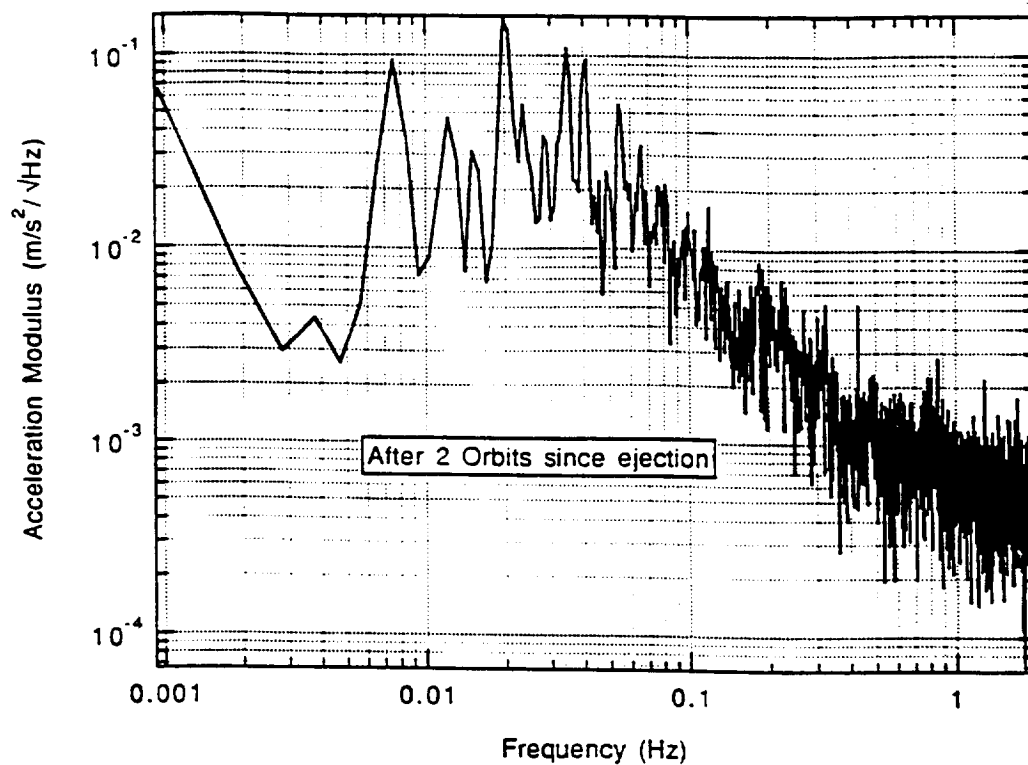


Figure 7a. Power spectrum of end-mass acceleration modulus
(2 orbits since ejection)

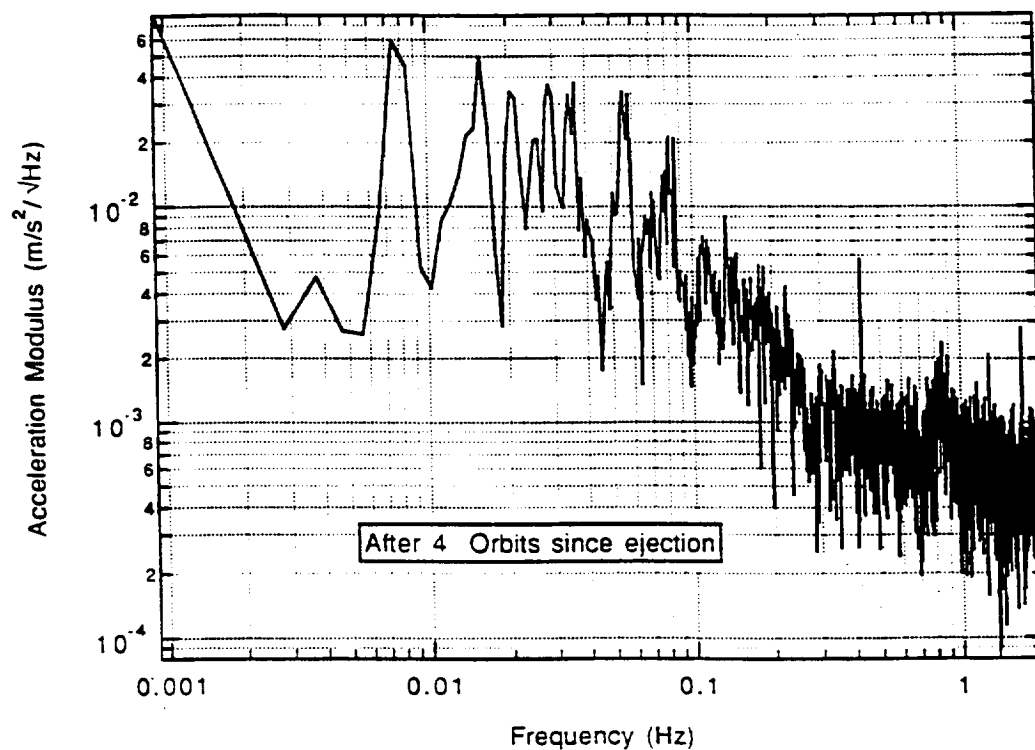


Figure 7b. Power spectrum of end-mass acceleration modulus
(4 orbits since ejection)

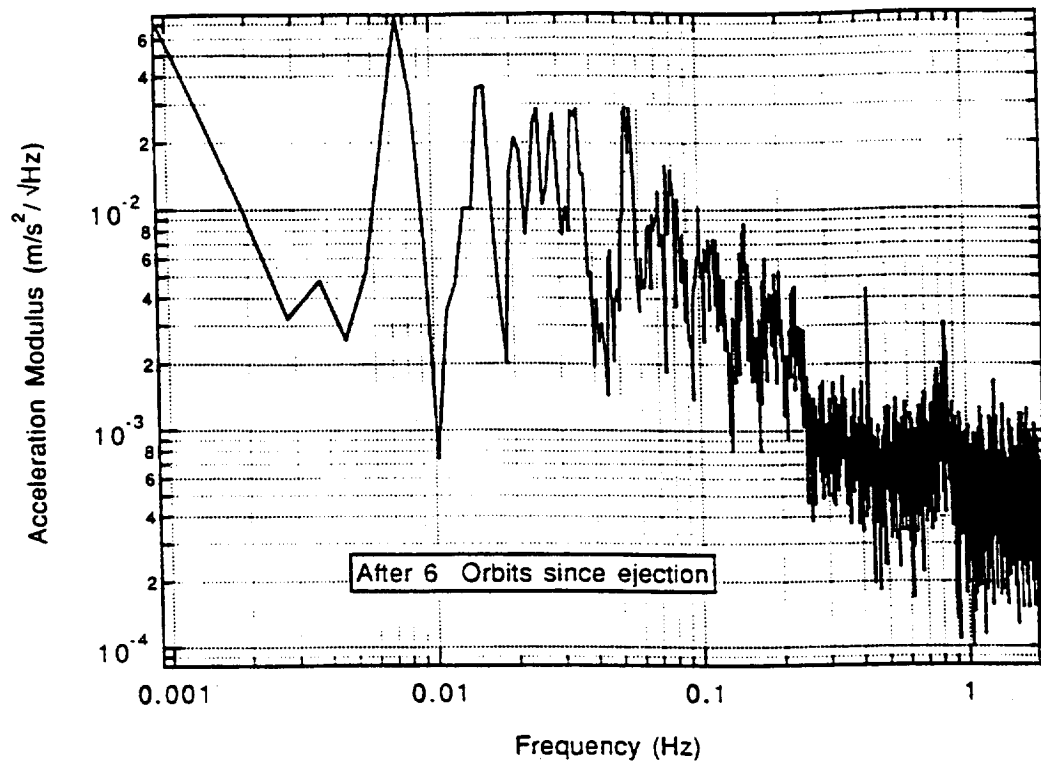


Figure 7c. Power spectrum of end-mass acceleration modulus (6 orbits since ejection)

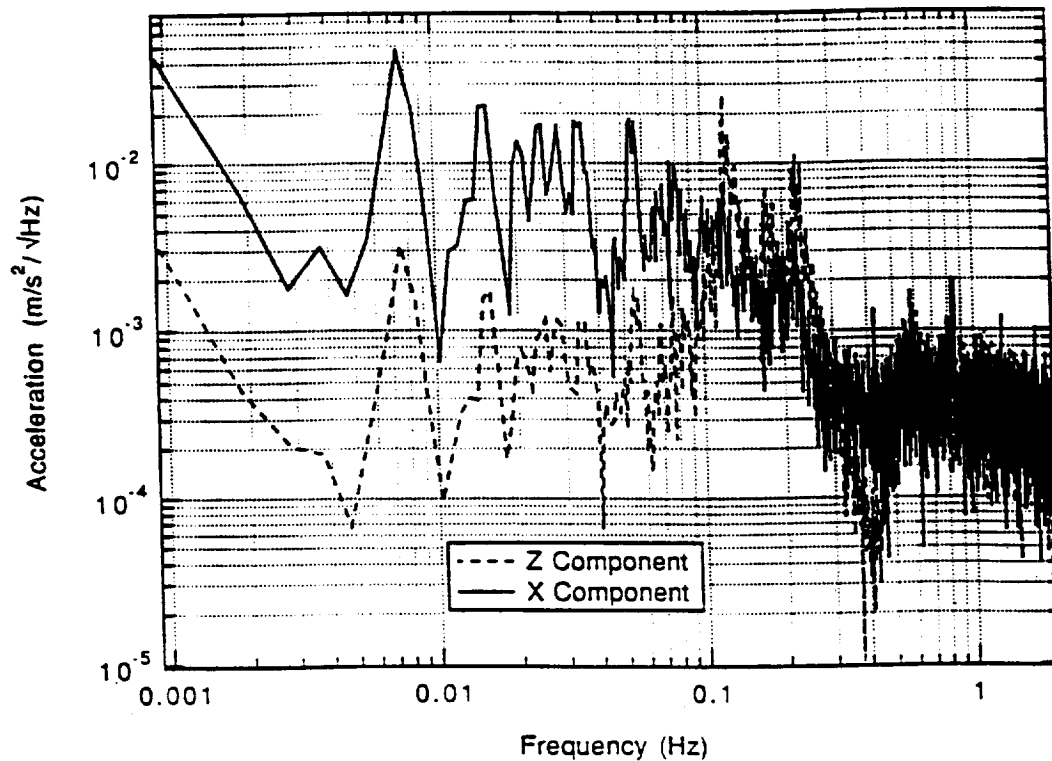


Figure 8. Power spectrum of end-mass acceleration x and z components (6 orbits since ejection)

CONCLUSIONS

This paper has analyzed the acceleration levels onboard SEDS-2 end-mass in order to assess the influence of the tether and the environmental perturbations on an hypothetical scientific platform. The estimation of the accelerations' power spectra has yielded a residual noise level of about $5 \times 10^{-4} \text{ m/s}^2/\sqrt{\text{Hz}}$. This value, however, cannot be generalized to all types of tethered satellites since some of the observed features are strictly related to SEDS-2 dynamics. Actually, some of the modes, like the longitudinal waves propagating through the tether from the deployer or the system's librations, can be actively damped. On the other hand, there are environmental perturbations like atmospheric density variations that are going to excite some tether oscillation modes which are very difficult to abate. Therefore, a thorough characterization of the "tether environment" and its dependence on environmental perturbations must be performed on a case by case basis in order to meet the missions' scientific objectives.

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4.0 Acknowledgments

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Appendix A

- 1) REFERENCE TABLE FOR SEDSAT_REF39
- 2) LIST OF CONTROL LAW PARAMETERS FOR SEDSAT_REF39

REFERENCE TABLE FOR SEDSAT_REF39

Note: Only the last three columns of this file are incorporated in the flight reference table.

Time (s)	Length (m)	Speed (m/s)	Turns	TurnRate	Brake Turns
0.00	0.500	1.470	3.	2.106	0.000
8.00	12.090	1.463	20.	2.097	0.000
16.00	23.665	1.457	37.	2.088	0.000
24.00	35.223	1.450	53.	2.079	0.000
32.00	46.762	1.444	70.	2.071	0.000
40.00	58.278	1.438	86.	2.063	0.000
48.00	69.771	1.433	103.	2.056	0.000
56.00	81.238	1.427	119.	2.049	0.000
64.00	92.677	1.422	136.	2.042	0.000
72.00	104.080	1.417	152.	2.035	0.000
80.00	115.460	1.412	168.	2.029	0.000
88.00	126.800	1.408	185.	2.023	0.000
96.00	138.110	1.404	201.	2.017	0.000
104.00	149.370	1.400	217.	2.012	0.000
112.00	160.590	1.396	233.	2.007	0.000
120.00	171.770	1.392	249.	2.003	0.000
128.00	182.910	1.389	265.	1.998	0.000
136.00	193.990	1.385	281.	1.994	0.000
144.00	205.050	1.383	297.	1.990	0.000
152.00	216.070	1.380	313.	1.987	0.000
160.00	227.070	1.377	329.	1.984	0.000
168.00	238.050	1.375	345.	1.981	0.000
176.00	249.020	1.373	361.	1.979	0.000
184.00	259.970	1.371	376.	1.977	0.000
192.00	270.910	1.370	392.	1.975	0.000
200.00	281.840	1.368	408.	1.974	0.000
208.00	292.770	1.367	424.	1.973	0.000
216.00	303.700	1.367	439.	1.972	0.000
224.00	314.630	1.366	455.	1.972	0.000
232.00	325.570	1.366	471.	1.972	0.000
240.00	336.520	1.366	487.	1.973	0.000
248.00	347.490	1.366	503.	1.974	0.000
256.00	358.470	1.367	518.	1.975	0.000
264.00	369.470	1.368	534.	1.977	0.000
272.00	380.500	1.369	550.	1.979	0.000
280.00	391.540	1.370	566.	1.981	0.000
288.00	402.590	1.372	582.	1.984	0.000
296.00	413.650	1.374	598.	1.987	0.000
304.00	424.720	1.376	614.	1.991	0.000
312.00	435.810	1.378	630.	1.995	0.000
320.00	446.900	1.381	646.	1.999	0.000
328.00	458.010	1.384	662.	2.004	0.000
336.00	469.130	1.387	679.	2.009	0.000
344.00	480.250	1.390	695.	2.015	0.000
352.00	491.390	1.394	711.	2.021	0.000
360.00	502.540	1.398	727.	2.027	0.000
368.00	513.690	1.403	743.	2.034	0.000
376.00	524.860	1.407	759.	2.041	0.000
384.00	536.030	1.412	776.	2.049	0.000
392.00	547.210	1.417	792.	2.057	0.000
400.00	558.400	1.423	808.	2.066	0.000
408.00	569.640	1.429	824.	2.075	0.000
416.00	580.990	1.435	841.	2.084	0.000
424.00	592.440	1.441	857.	2.093	0.000
432.00	603.970	1.447	874.	2.103	0.000
440.00	615.590	1.453	891.	2.113	0.000
448.00	627.290	1.460	908.	2.123	0.000
456.00	639.070	1.467	925.	2.134	0.000

464.00	650.910	1.474	943.	2.145	0.000
472.00	662.820	1.481	960.	2.156	0.000
480.00	674.790	1.489	977.	2.168	0.000
488.00	686.810	1.497	995.	2.180	0.000
496.00	698.870	1.505	1012.	2.192	0.000
504.00	710.980	1.513	1030.	2.205	0.000
512.00	723.120	1.521	1048.	2.218	0.000
520.00	735.290	1.530	1065.	2.232	0.000
528.00	747.490	1.539	1083.	2.245	0.000
536.00	759.710	1.549	1101.	2.260	0.000
544.00	772.030	1.559	1119.	2.275	0.000
552.00	784.460	1.568	1137.	2.289	0.000
560.00	797.000	1.578	1155.	2.304	0.000
568.00	809.650	1.588	1174.	2.319	0.000
576.00	822.400	1.597	1193.	2.334	0.000
584.00	835.250	1.607	1211.	2.350	0.000
592.00	848.200	1.618	1230.	2.365	0.000
600.00	861.240	1.628	1249.	2.381	0.000
608.00	874.360	1.638	1269.	2.397	0.000
616.00	887.570	1.649	1288.	2.413	0.000
624.00	900.860	1.660	1307.	2.430	0.000
632.00	914.220	1.671	1327.	2.446	0.000
640.00	927.660	1.682	1347.	2.464	0.000
648.00	941.160	1.693	1366.	2.481	0.000
656.00	954.730	1.704	1386.	2.499	0.000
664.00	968.350	1.716	1406.	2.517	0.000
672.00	982.050	1.728	1426.	2.535	0.000
680.00	995.860	1.740	1447.	2.554	0.000
688.00	1009.800	1.752	1467.	2.572	0.000
696.00	1023.800	1.764	1488.	2.591	0.000
704.00	1038.000	1.776	1508.	2.610	0.000
712.00	1052.200	1.788	1529.	2.628	0.000
720.00	1066.600	1.801	1550.	2.647	0.000
728.00	1081.100	1.813	1572.	2.666	0.000
736.00	1095.600	1.825	1593.	2.685	0.000
744.00	1110.300	1.837	1615.	2.704	0.000
752.00	1125.100	1.849	1637.	2.723	0.000
760.00	1140.000	1.862	1658.	2.742	0.000
768.00	1154.900	1.874	1680.	2.761	0.000
776.00	1170.000	1.887	1703.	2.781	0.000
784.00	1185.100	1.899	1725.	2.800	0.000
792.00	1200.400	1.912	1747.	2.820	0.000
800.00	1215.700	1.925	1770.	2.840	0.000
808.00	1231.100	1.938	1793.	2.860	0.000
816.00	1246.600	1.950	1816.	2.880	0.000
824.00	1262.300	1.963	1839.	2.900	0.000
832.00	1278.000	1.976	1862.	2.920	0.000
840.00	1293.900	1.989	1886.	2.940	0.000
848.00	1309.800	2.002	1909.	2.961	0.000
856.00	1325.900	2.015	1933.	2.981	0.000
864.00	1342.100	2.028	1957.	3.001	0.000
872.00	1358.300	2.041	1981.	3.022	0.000
880.00	1374.700	2.053	2005.	3.042	0.000
888.00	1391.200	2.066	2030.	3.062	0.000
896.00	1407.800	2.079	2054.	3.083	0.000
904.00	1424.500	2.092	2079.	3.103	0.000
912.00	1441.300	2.105	2104.	3.123	0.000
920.00	1458.200	2.118	2129.	3.144	0.000
928.00	1475.200	2.131	2154.	3.164	0.000
936.00	1492.300	2.143	2180.	3.184	0.000
944.00	1509.500	2.156	2205.	3.205	0.000
952.00	1526.800	2.169	2231.	3.225	0.000
960.00	1544.200	2.181	2257.	3.245	0.000
968.00	1561.700	2.194	2283.	3.265	0.000
976.00	1579.300	2.206	2309.	3.286	0.000
984.00	1597.000	2.219	2335.	3.306	0.000

992.00	1614.800	2.231	2362.	3.326	0.000
1000.00	1632.700	2.244	2389.	3.346	0.000
1008.00	1650.700	2.257	2415.	3.366	0.000
1016.00	1668.800	2.269	2442.	3.386	0.000
1024.00	1687.000	2.281	2470.	3.407	0.000
1032.00	1705.300	2.294	2497.	3.427	0.000
1040.00	1723.700	2.306	2524.	3.447	0.000
1048.00	1742.200	2.319	2552.	3.467	0.000
1056.00	1760.800	2.331	2580.	3.487	0.000
1064.00	1779.500	2.343	2608.	3.507	0.000
1072.00	1798.400	2.355	2636.	3.527	0.000
1080.00	1817.300	2.368	2665.	3.547	0.000
1088.00	1836.300	2.379	2693.	3.567	0.000
1096.00	1855.400	2.391	2722.	3.586	0.000
1104.00	1874.500	2.403	2750.	3.606	0.000
1112.00	1893.800	2.415	2779.	3.625	0.000
1120.00	1913.100	2.427	2808.	3.645	0.000
1128.00	1932.600	2.438	2838.	3.664	0.000
1136.00	1952.100	2.450	2867.	3.683	0.000
1144.00	1971.700	2.461	2896.	3.702	0.000
1152.00	1991.400	2.473	2926.	3.721	0.000
1160.00	2011.200	2.484	2956.	3.740	0.000
1168.00	2031.200	2.495	2986.	3.759	0.000
1176.00	2051.200	2.506	3016.	3.778	0.000
1184.00	2071.300	2.517	3046.	3.797	0.000
1192.00	2091.500	2.528	3077.	3.815	0.000
1200.00	2111.800	2.539	3107.	3.834	0.000
1208.00	2132.200	2.550	3138.	3.852	0.000
1216.00	2152.700	2.561	3169.	3.871	0.000
1224.00	2173.200	2.572	3200.	3.889	0.000
1232.00	2193.800	2.583	3231.	3.908	0.000
1240.00	2214.500	2.593	3263.	3.926	0.000
1248.00	2235.300	2.604	3294.	3.944	0.000
1256.00	2256.200	2.614	3326.	3.962	0.000
1264.00	2277.100	2.625	3358.	3.980	0.000
1272.00	2298.100	2.635	3389.	3.998	0.000
1280.00	2319.200	2.645	3421.	4.015	0.000
1288.00	2340.400	2.655	3454.	4.033	0.000
1296.00	2361.600	2.665	3486.	4.050	0.000
1304.00	2383.000	2.675	3518.	4.068	0.000
1312.00	2404.400	2.685	3551.	4.085	0.000
1320.00	2426.000	2.695	3584.	4.102	0.000
1328.00	2447.600	2.705	3617.	4.120	0.000
1336.00	2469.300	2.714	3650.	4.137	0.000
1344.00	2491.100	2.724	3683.	4.154	0.000
1352.00	2513.000	2.733	3716.	4.171	0.000
1360.00	2534.900	2.743	3750.	4.187	0.000
1368.00	2556.900	2.752	3783.	4.204	0.000
1376.00	2578.900	2.761	3817.	4.221	0.000
1384.00	2601.000	2.771	3851.	4.238	0.000
1392.00	2623.200	2.780	3885.	4.254	0.000
1400.00	2645.500	2.789	3919.	4.271	0.000
1408.00	2667.800	2.798	3953.	4.287	0.000
1416.00	2690.200	2.807	3987.	4.303	0.000
1424.00	2712.600	2.816	4022.	4.320	0.000
1432.00	2735.200	2.825	4056.	4.336	0.000
1440.00	2757.800	2.833	4091.	4.352	0.000
1448.00	2780.500	2.842	4126.	4.368	0.000
1456.00	2803.300	2.851	4161.	4.383	0.000
1464.00	2826.200	2.859	4196.	4.399	0.000
1472.00	2849.100	2.867	4231.	4.415	0.000
1480.00	2872.100	2.876	4267.	4.430	0.000
1488.00	2895.200	2.884	4303.	4.446	0.000
1496.00	2918.300	2.892	4338.	4.461	0.000
1504.00	2941.500	2.900	4374.	4.477	0.000
1512.00	2964.700	2.908	4410.	4.492	0.000

1520.00	2988.000	2.917	4446.	4.508	0.000
1528.00	3011.300	2.925	4482.	4.523	0.000
1536.00	3034.700	2.933	4518.	4.538	0.000
1544.00	3058.200	2.941	4554.	4.554	0.000
1552.00	3081.700	2.948	4591.	4.569	0.000
1560.00	3105.400	2.956	4627.	4.584	0.000
1568.00	3129.000	2.964	4664.	4.599	0.000
1576.00	3152.800	2.972	4701.	4.614	0.000
1584.00	3176.600	2.979	4738.	4.629	0.000
1592.00	3200.400	2.987	4775.	4.643	0.000
1600.00	3224.400	2.994	4812.	4.658	0.000
1608.00	3248.400	3.002	4850.	4.673	0.000
1616.00	3272.500	3.009	4887.	4.687	0.000
1624.00	3296.600	3.016	4925.	4.702	0.000
1632.00	3320.700	3.024	4962.	4.716	0.000
1640.00	3345.000	3.031	5000.	4.731	0.000
1648.00	3369.200	3.038	5038.	4.746	0.000
1656.00	3393.600	3.046	5076.	4.760	0.000
1664.00	3418.000	3.053	5114.	4.775	0.000
1672.00	3442.400	3.060	5152.	4.789	0.000
1680.00	3466.900	3.067	5191.	4.804	0.000
1688.00	3491.400	3.074	5229.	4.818	0.000
1696.00	3516.100	3.081	5268.	4.833	0.000
1704.00	3540.700	3.088	5307.	4.847	0.000
1712.00	3565.500	3.095	5345.	4.862	0.000
1720.00	3590.300	3.102	5384.	4.876	0.000
1728.00	3615.100	3.109	5423.	4.890	0.000
1736.00	3640.000	3.116	5463.	4.905	0.000
1744.00	3665.000	3.123	5502.	4.919	0.000
1752.00	3690.000	3.130	5541.	4.933	0.000
1760.00	3715.100	3.137	5581.	4.948	0.000
1768.00	3740.200	3.144	5621.	4.962	0.000
1776.00	3765.400	3.150	5660.	4.976	0.000
1784.00	3790.600	3.157	5700.	4.990	0.000
1792.00	3815.900	3.164	5740.	5.005	0.000
1800.00	3841.200	3.171	5780.	5.019	0.000
1808.00	3866.600	3.178	5820.	5.034	0.000
1816.00	3892.100	3.184	5861.	5.048	0.000
1824.00	3917.600	3.191	5901.	5.063	0.000
1832.00	3943.100	3.198	5942.	5.077	0.000
1840.00	3968.700	3.205	5982.	5.092	0.000
1848.00	3994.400	3.211	6023.	5.106	0.000
1856.00	4020.100	3.218	6064.	5.121	0.000
1864.00	4045.900	3.225	6105.	5.136	0.000
1872.00	4071.700	3.232	6146.	5.151	0.000
1880.00	4097.600	3.239	6188.	5.166	0.000
1888.00	4123.500	3.246	6229.	5.180	0.000
1896.00	4149.500	3.253	6270.	5.195	0.000
1904.00	4175.600	3.260	6312.	5.210	0.000
1912.00	4201.700	3.266	6354.	5.225	0.000
1920.00	4227.900	3.273	6396.	5.240	0.000
1928.00	4254.100	3.280	6438.	5.256	0.000
1936.00	4280.400	3.287	6480.	5.271	0.000
1944.00	4306.700	3.294	6522.	5.286	0.000
1952.00	4333.100	3.301	6564.	5.301	0.000
1960.00	4359.500	3.308	6607.	5.317	0.000
1968.00	4386.000	3.315	6649.	5.332	0.000
1976.00	4412.500	3.322	6692.	5.348	0.000
1984.00	4439.100	3.329	6735.	5.363	0.000
1992.00	4465.800	3.336	6778.	5.378	0.000
2000.00	4492.500	3.343	6821.	5.394	0.000
2008.00	4519.200	3.350	6864.	5.410	0.000
2016.00	4546.000	3.357	6907.	5.426	0.000
2024.00	4572.900	3.364	6951.	5.442	0.000
2032.00	4599.900	3.372	6995.	5.458	0.000
2040.00	4626.900	3.379	7038.	5.474	0.000

2048.00	4654.000	3.386	7082.	5.491	0.000
2056.00	4681.100	3.394	7126.	5.507	0.000
2064.00	4708.300	3.401	7170.	5.524	0.000
2072.00	4735.600	3.409	7215.	5.541	0.000
2080.00	4762.900	3.417	7259.	5.558	0.000
2088.00	4790.300	3.424	7304.	5.575	0.000
2096.00	4817.700	3.432	7348.	5.593	0.000
2104.00	4845.200	3.440	7393.	5.610	0.000
2112.00	4872.700	3.448	7438.	5.627	0.000
2120.00	4900.300	3.456	7483.	5.645	0.000
2128.00	4928.000	3.464	7528.	5.663	0.000
2136.00	4955.600	3.471	7574.	5.680	0.000
2144.00	4983.400	3.479	7619.	5.698	0.000
2152.00	5011.300	3.487	7665.	5.716	0.000
2160.00	5039.200	3.496	7710.	5.735	0.000
2168.00	5067.200	3.504	7756.	5.753	0.000
2176.00	5095.300	3.512	7803.	5.772	0.000
2184.00	5123.500	3.521	7849.	5.791	0.000
2192.00	5151.700	3.529	7895.	5.810	0.000
2200.00	5180.000	3.538	7942.	5.830	0.000
2208.00	5208.300	3.547	7989.	5.849	0.000
2216.00	5236.800	3.556	8036.	5.869	0.000
2224.00	5265.300	3.565	8083.	5.889	0.000
2232.00	5293.800	3.573	8130.	5.909	0.000
2240.00	5322.500	3.582	8177.	5.929	0.000
2248.00	5351.100	3.592	8225.	5.950	0.000
2256.00	5379.900	3.601	8272.	5.970	0.000
2264.00	5408.700	3.610	8320.	5.991	0.000
2272.00	5437.500	3.619	8368.	6.012	0.000
2280.00	5466.500	3.628	8416.	6.033	0.000
2288.00	5495.500	3.638	8464.	6.054	0.000
2296.00	5524.700	3.648	8513.	6.076	0.000
2304.00	5553.900	3.658	8562.	6.098	0.000
2312.00	5583.200	3.668	8611.	6.120	0.000
2320.00	5612.600	3.678	8660.	6.143	0.000
2328.00	5642.100	3.688	8709.	6.166	0.000
2336.00	5671.700	3.698	8758.	6.189	0.000
2344.00	5701.400	3.708	8808.	6.212	0.000
2352.00	5731.100	3.719	8858.	6.236	0.000
2360.00	5760.900	3.730	8908.	6.260	0.000
2368.00	5790.800	3.740	8958.	6.284	0.000
2376.00	5820.800	3.751	9009.	6.308	0.000
2384.00	5850.800	3.762	9059.	6.332	0.000
2392.00	5880.900	3.773	9110.	6.357	0.000
2400.00	5911.100	3.784	9161.	6.382	0.000
2408.00	5941.300	3.795	9212.	6.407	0.000
2416.00	5971.700	3.806	9263.	6.432	0.000
2424.00	6002.100	3.818	9314.	6.458	0.000
2432.00	6032.700	3.829	9366.	6.484	0.000
2440.00	6063.400	3.841	9418.	6.511	0.000
2448.00	6094.300	3.853	9471.	6.538	0.000
2456.00	6125.200	3.865	9523.	6.565	0.000
2464.00	6156.200	3.877	9576.	6.593	0.000
2472.00	6187.300	3.890	9629.	6.620	0.000
2480.00	6218.500	3.902	9682.	6.648	0.000
2488.00	6249.800	3.915	9735.	6.677	0.000
2496.00	6281.200	3.928	9789.	6.706	0.000
2504.00	6312.700	3.940	9843.	6.735	0.000
2512.00	6344.200	3.953	9896.	6.764	0.000
2520.00	6375.900	3.967	9951.	6.794	0.000
2528.00	6407.600	3.980	10005.	6.824	0.000
2536.00	6439.400	3.993	10060.	6.854	0.000
2544.00	6471.300	4.006	10114.	6.884	0.000
2552.00	6503.400	4.020	10169.	6.915	0.000
2560.00	6535.600	4.034	10225.	6.947	0.000
2568.00	6567.900	4.048	10281.	6.979	0.000

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2576.00	6600.400	4.062	10337.	7.011	0.000
2584.00	6633.000	4.076	10393.	7.043	0.000
2592.00	6665.700	4.091	10449.	7.076	0.000
2600.00	6698.600	4.106	10506.	7.110	0.000
2608.00	6731.500	4.120	10563.	7.143	0.000
2616.00	6764.600	4.135	10621.	7.178	0.000
2624.00	6797.800	4.150	10678.	7.212	0.000
2632.00	6831.100	4.166	10736.	7.247	0.000
2640.00	6864.500	4.181	10795.	7.282	0.000
2648.00	6897.900	4.197	10853.	7.318	0.000
2656.00	6931.500	4.212	10911.	7.354	0.000
2664.00	6965.200	4.228	10970.	7.390	0.000
2672.00	6999.000	4.244	11029.	7.427	0.000
2680.00	7032.900	4.260	11089.	7.464	0.000
2688.00	7067.100	4.277	11149.	7.502	0.000
2696.00	7101.300	4.293	11209.	7.540	0.000
2704.00	7135.800	4.310	11269.	7.578	0.000
2712.00	7170.300	4.327	11330.	7.617	0.000
2720.00	7205.100	4.344	11391.	7.657	0.000
2728.00	7239.900	4.361	11453.	7.697	0.000
2736.00	7275.000	4.378	11515.	7.737	0.000
2744.00	7310.100	4.396	11577.	7.778	0.000
2752.00	7345.400	4.414	11639.	7.819	0.000
2760.00	7380.800	4.432	11702.	7.861	0.000
2768.00	7416.400	4.450	11765.	7.903	0.000
2776.00	7452.000	4.468	11828.	7.946	0.000
2784.00	7487.800	4.486	11892.	7.989	0.000
2792.00	7523.700	4.505	11956.	8.033	0.000
2800.00	7559.700	4.524	12020.	8.076	0.000
2808.00	7595.900	4.543	12085.	8.121	0.000
2816.00	7632.200	4.562	12150.	8.166	0.000
2824.00	7668.800	4.581	12216.	8.211	0.000
2832.00	7705.500	4.600	12281.	8.258	0.000
2840.00	7742.400	4.620	12348.	8.304	0.000
2848.00	7779.500	4.640	12414.	8.351	0.000
2856.00	7816.800	4.660	12482.	8.399	0.000
2864.00	7854.200	4.680	12549.	8.447	0.000
2872.00	7891.800	4.700	12617.	8.496	0.000
2880.00	7929.500	4.721	12685.	8.545	0.000
2888.00	7967.400	4.742	12754.	8.595	0.000
2896.00	8005.500	4.762	12823.	8.645	0.000
2904.00	8043.700	4.784	12892.	8.696	0.000
2912.00	8082.000	4.805	12962.	8.748	0.000
2920.00	8120.500	4.826	13032.	8.799	0.000
2928.00	8159.100	4.848	13103.	8.852	0.000
2936.00	8197.800	4.870	13173.	8.905	0.000
2944.00	8236.800	4.892	13245.	8.958	0.000
2952.00	8276.000	4.914	13316.	9.013	0.000
2960.00	8315.300	4.936	13389.	9.067	0.000
2968.00	8354.900	4.959	13461.	9.123	0.000
2976.00	8394.700	4.982	13535.	9.179	0.000
2984.00	8434.700	5.004	13608.	9.235	0.000
2992.00	8474.900	5.028	13683.	9.293	0.000
3000.00	8515.300	5.051	13757.	9.351	0.000
3008.00	8555.900	5.074	13833.	9.409	0.000
3016.00	8596.600	5.098	13908.	9.468	0.000
3024.00	8637.500	5.122	13984.	9.528	0.000
3032.00	8678.600	5.146	14061.	9.588	0.000
3040.00	8719.900	5.170	14138.	9.649	0.000
3048.00	8761.300	5.194	14215.	9.711	0.000
3056.00	8802.900	5.219	14293.	9.773	0.000
3064.00	8844.700	5.244	14371.	9.836	0.000
3072.00	8886.600	5.269	14450.	9.900	0.000
3080.00	8928.800	5.294	14529.	9.964	0.000
3088.00	8971.200	5.319	14609.	10.029	0.000
3096.00	9013.800	5.345	14689.	10.094	0.000

3104.00	9056.700	5.370	14771.	10.161	0.000
3112.00	9099.800	5.396	14852.	10.228	0.000
3120.00	9143.100	5.422	14934.	10.296	0.000
3128.00	9186.700	5.448	15017.	10.364	0.000
3136.00	9230.400	5.475	15100.	10.433	0.000
3144.00	9274.400	5.501	15184.	10.503	0.000
3152.00	9318.600	5.528	15269.	10.574	0.000
3160.00	9363.000	5.555	15354.	10.645	0.000
3168.00	9407.500	5.582	15439.	10.717	0.000
3176.00	9452.300	5.610	15525.	10.790	0.000
3184.00	9497.300	5.637	15612.	10.864	0.000
3192.00	9542.400	5.665	15699.	10.939	0.000
3200.00	9587.700	5.693	15786.	11.014	0.000
3208.00	9633.300	5.721	15875.	11.090	0.000
3216.00	9679.100	5.749	15964.	11.167	0.000
3224.00	9725.200	5.778	16053.	11.244	0.000
3232.00	9771.500	5.806	16143.	11.323	0.000
3240.00	9818.100	5.835	16234.	11.402	0.000
3248.00	9864.900	5.864	16326.	11.482	0.000
3256.00	9912.000	5.893	16418.	11.563	0.000
3264.00	9959.300	5.922	16511.	11.645	0.000
3272.00	10007.000	5.951	16605.	11.728	0.000
3280.00	10055.000	5.981	16700.	11.811	0.000
3288.00	10103.000	6.011	16795.	11.896	0.000
3296.00	10151.000	6.041	16890.	11.981	0.000
3304.00	10199.000	6.071	16985.	12.067	0.000
3312.00	10248.000	6.101	17083.	12.154	0.000
3320.00	10297.000	6.132	17180.	12.243	0.000
3328.00	10346.000	6.163	17278.	12.331	0.000
3336.00	10395.000	6.194	17376.	12.421	0.000
3344.00	10445.000	6.225	17477.	12.513	0.000
3352.00	10495.000	6.256	17577.	12.605	0.000
3360.00	10545.000	6.287	17678.	12.697	0.000
3368.00	10595.000	6.319	17779.	12.791	0.000
3376.00	10646.000	6.350	17883.	12.886	0.000
3384.00	10697.000	6.382	17986.	12.982	0.000
3392.00	10748.000	6.414	18090.	13.079	0.000
3400.00	10800.000	6.446	18196.	13.177	0.000
3408.00	10852.000	6.479	18303.	13.276	0.000
3416.00	10904.000	6.511	18410.	13.376	0.000
3424.00	10956.000	6.544	18516.	13.477	0.000
3432.00	11008.000	6.576	18624.	13.579	0.000
3440.00	11061.000	6.609	18733.	13.682	0.000
3448.00	11114.000	6.643	18843.	13.787	0.000
3456.00	11167.000	6.676	18953.	13.893	0.000
3464.00	11221.000	6.709	19066.	14.000	0.000
3472.00	11275.000	6.743	19179.	14.109	0.000
3480.00	11329.000	6.777	19292.	14.218	0.000
3488.00	11383.000	6.811	19405.	14.328	0.000
3496.00	11437.000	6.845	19519.	14.440	0.000
3504.00	11492.000	6.879	19635.	14.552	0.000
3512.00	11548.000	6.913	19754.	14.667	0.000
3520.00	11603.000	6.948	19871.	14.782	0.000
3528.00	11659.000	6.982	19990.	14.899	0.000
3536.00	11715.000	7.017	20110.	15.017	0.000
3544.00	11771.000	7.052	20230.	15.136	0.000
3552.00	11828.000	7.087	20352.	15.257	0.000
3560.00	11885.000	7.122	20475.	15.379	0.000
3568.00	11942.000	7.157	20598.	15.503	0.000
3576.00	11999.000	7.193	20722.	15.628	0.000
3584.00	12057.000	7.228	20848.	15.755	0.000
3592.00	12115.000	7.264	20975.	15.883	0.000
3600.00	12173.000	7.300	21102.	16.013	0.000
3608.00	12231.000	7.336	21229.	16.144	0.000
3616.00	12290.000	7.372	21359.	16.277	0.000
3624.00	12349.000	7.408	21490.	16.411	0.000

3632.00	12409.000	7.445	21623.	16.547	0.000
3640.00	12468.000	7.481	21754.	16.684	0.000
3648.00	12528.000	7.517	21888.	16.823	0.000
3656.00	12589.000	7.554	22025.	16.964	0.000
3664.00	12649.000	7.590	22160.	17.106	0.000
3672.00	12710.000	7.627	22298.	17.250	0.000
3680.00	12771.000	7.664	22436.	17.396	0.000
3688.00	12833.000	7.701	22577.	17.544	0.000
3696.00	12895.000	7.738	22719.	17.694	0.000
3704.00	12957.000	7.775	22861.	17.846	0.000
3712.00	13019.000	7.813	23003.	18.000	0.000
3720.00	13082.000	7.850	23149.	18.156	0.000
3728.00	13145.000	7.888	23295.	18.315	0.000
3736.00	13208.000	7.926	23441.	18.475	0.000
3744.00	13271.000	7.964	23588.	18.637	0.000
3752.00	13335.000	8.002	23738.	18.802	0.000
3760.00	13399.000	8.041	23889.	18.969	0.000
3768.00	13463.000	8.079	24040.	19.137	0.000
3776.00	13528.000	8.117	24195.	19.308	0.000
3784.00	13593.000	8.155	24350.	19.481	0.000
3792.00	13658.000	8.193	24505.	19.657	0.000
3800.00	13723.000	8.231	24661.	19.834	0.000
3808.00	13789.000	8.270	24821.	20.014	0.000
3816.00	13855.000	8.308	24981.	20.196	0.000
3824.00	13922.000	8.346	25144.	20.382	0.000
3832.00	13989.000	8.384	25308.	20.570	0.000
3840.00	14056.000	8.423	25473.	20.760	0.000
3848.00	14124.000	8.461	25641.	20.954	0.000
3856.00	14193.000	8.499	25812.	21.152	0.000
3864.00	14261.000	8.537	25982.	21.350	0.000
3872.00	14330.000	8.576	26155.	21.553	0.000
3880.00	14400.000	8.614	26331.	21.760	0.000
3888.00	14469.000	8.652	26506.	21.968	0.000
3896.00	14539.000	8.691	26684.	22.181	0.000
3904.00	14609.000	8.729	26863.	22.397	0.000
3912.00	14679.000	8.768	27043.	22.615	0.000
3920.00	14749.000	8.806	27224.	22.837	0.000
3928.00	14819.000	8.845	27406.	23.062	0.000
3936.00	14890.000	8.883	27592.	23.291	0.000
3944.00	14961.000	8.922	27779.	23.524	0.000
3952.00	15032.000	8.960	27967.	23.761	0.000
3960.00	15104.000	8.998	28158.	24.003	0.000
3968.00	15176.000	9.037	28351.	24.248	0.000
3976.00	15248.000	9.075	28544.	24.497	0.000
3984.00	15321.000	9.114	28742.	24.752	0.000
3992.00	15394.000	9.152	28941.	25.012	0.000
4000.00	15467.000	9.190	29141.	25.275	0.000
4008.00	15541.000	9.227	29345.	25.541	0.024
4016.00	15615.000	9.262	29551.	25.805	0.050
4024.00	15689.000	9.293	29758.	26.066	0.075
4032.00	15763.000	9.323	29966.	26.324	0.101
4040.00	15838.000	9.349	30178.	26.581	0.128
4048.00	15913.000	9.372	30392.	26.834	0.155
4056.00	15988.000	9.392	30608.	27.084	0.183
4064.00	16063.000	9.409	30825.	27.328	0.211
4072.00	16139.000	9.422	31046.	27.569	0.240
4080.00	16214.000	9.431	31267.	27.802	0.269
4088.00	16289.000	9.436	31489.	28.029	0.299
4096.00	16365.000	9.438	31715.	28.250	0.329
4104.00	16440.000	9.435	31941.	28.462	0.359
4112.00	16516.000	9.427	32171.	28.668	0.390
4120.00	16591.000	9.415	32400.	28.861	0.422
4128.00	16667.000	9.398	32634.	29.048	0.453
4136.00	16742.000	9.376	32867.	29.222	0.485
4144.00	16817.000	9.349	33101.	29.384	0.518
4152.00	16891.000	9.317	33335.	29.531	0.550

4160.00	16966.000	9.279	33574.	29.669	0.584
4168.00	17040.000	9.236	33811.	29.790	0.617
4176.00	17113.000	9.187	34048.	29.894	0.651
4184.00	17187.000	9.132	34290.	29.987	0.685
4192.00	17259.000	9.072	34527.	30.058	0.719
4200.00	17332.000	9.005	34770.	30.116	0.753
4208.00	17404.000	8.933	35012.	30.156	0.788
4216.00	17475.000	8.855	35253.	30.174	0.823
4224.00	17545.000	8.772	35493.	30.172	0.858
4232.00	17615.000	8.682	35734.	30.152	0.893
4240.00	17684.000	8.587	35975.	30.111	0.929
4248.00	17752.000	8.487	36215.	30.048	0.965
4256.00	17820.000	8.381	36457.	29.968	1.001
4264.00	17886.000	8.270	36694.	29.861	1.037
4272.00	17952.000	8.154	36933.	29.737	1.073
4280.00	18017.000	8.033	37172.	29.592	1.109
4288.00	18081.000	7.908	37409.	29.426	1.145
4296.00	18143.000	7.779	37640.	29.235	1.182
4304.00	18205.000	7.646	37875.	29.028	1.218
4312.00	18266.000	7.509	38107.	28.803	1.255
4320.00	18325.000	7.370	38335.	28.554	1.291
4328.00	18384.000	7.228	38565.	28.293	1.328
4336.00	18441.000	7.084	38789.	28.010	1.365
4344.00	18497.000	6.938	39011.	27.712	1.401
4352.00	18552.000	6.790	39232.	27.401	1.438
4360.00	18606.000	6.642	39451.	27.078	1.475
4368.00	18658.000	6.493	39664.	26.738	1.511
4376.00	18710.000	6.344	39880.	26.393	1.548
4384.00	18760.000	6.196	40089.	26.035	1.584
4392.00	18809.000	6.048	40296.	25.670	1.621
4400.00	18856.000	5.902	40496.	25.295	1.657
4408.00	18903.000	5.756	40698.	24.921	1.694
4416.00	18949.000	5.612	40899.	24.541	1.733
4424.00	18993.000	5.469	41092.	24.149	1.773
4432.00	19036.000	5.326	41283.	23.748	1.815
4440.00	19078.000	5.184	41471.	23.339	1.858
4448.00	19119.000	5.042	41656.	22.919	1.903
4456.00	19159.000	4.900	41839.	22.489	1.949
4464.00	19197.000	4.759	42014.	22.043	1.996
4472.00	19235.000	4.617	42191.	21.591	2.045
4480.00	19271.000	4.476	42360.	21.123	2.094
4488.00	19307.000	4.336	42531.	20.650	2.145
4496.00	19341.000	4.195	42694.	20.162	2.196
4504.00	19374.000	4.056	42853.	19.665	2.249
4512.00	19406.000	3.918	43009.	19.160	2.302
4520.00	19436.000	3.780	43156.	18.643	2.356
4528.00	19466.000	3.645	43305.	18.126	2.411
4536.00	19495.000	3.510	43449.	17.604	2.467
4544.00	19522.000	3.378	43585.	17.074	2.523
4552.00	19549.000	3.248	43722.	16.547	2.579
4560.00	19574.000	3.120	43850.	16.015	2.636
4568.00	19599.000	2.994	43979.	15.488	2.693
4576.00	19622.000	2.871	44098.	14.958	2.751
4584.00	19645.000	2.751	44219.	14.436	2.809
4592.00	19666.000	2.634	44329.	13.913	2.867
4600.00	19687.000	2.519	44441.	13.398	2.925
4608.00	19706.000	2.408	44542.	12.886	2.983
4616.00	19725.000	2.299	44644.	12.383	3.041
4624.00	19743.000	2.194	44741.	11.886	3.099
4632.00	19760.000	2.091	44833.	11.395	3.157
4640.00	19777.000	1.992	44926.	10.916	3.215
4648.00	19792.000	1.895	45009.	10.439	3.272
4656.00	19807.000	1.801	45092.	9.973	3.329
4664.00	19821.000	1.709	45169.	9.513	3.385
4672.00	19834.000	1.620	45242.	9.059	3.441
4680.00	19847.000	1.533	45315.	8.615	3.496

4688.00	19859.000	1.449	45382.	8.176	3.551
4696.00	19870.000	1.367	45444.	7.743	3.605
4704.00	19881.000	1.286	45507.	7.316	3.658
4712.00	19891.000	1.207	45564.	6.894	3.710
4720.00	19900.000	1.130	45615.	6.476	3.762
4728.00	19909.000	1.055	45667.	6.062	3.812
4736.00	19917.000	0.980	45713.	5.651	3.861
4744.00	19925.000	0.907	45759.	5.243	3.909
4752.00	19932.000	0.834	45800.	4.835	3.956
4760.00	19938.000	0.762	45835.	4.427	4.002
4768.00	19944.000	0.690	45870.	4.018	4.046
4776.00	19949.000	0.618	45899.	3.606	4.089
4784.00	19954.000	0.545	45928.	3.191	4.131
4792.00	19958.000	0.472	45951.	2.767	4.171
4800.00	19961.000	0.398	45969.	2.333	4.209
4808.00	19964.000	0.322	45987.	1.891	4.243
4816.00	19966.000	0.248	45998.	1.455	4.270
4824.00	19968.000	0.177	46010.	1.039	4.290
4832.00	19969.000	0.113	46016.	0.663	4.303
4840.00	19970.000	0.058	46022.	0.344	4.310
4848.00	19970.000	0.017	46022.	0.099	4.311
4856.00	19970.000	0.000	46022.	0.000	4.311
4864.00	19970.000	0.000	46022.	0.000	4.311
4872.00	19970.000	0.000	46022.	0.000	4.311
4880.00	19970.000	0.000	46022.	0.000	4.311
4888.00	19970.000	0.000	46022.	0.000	4.311
4896.00	19970.000	0.000	46022.	0.000	4.311
4904.00	19970.000	0.000	46022.	0.000	4.311
4912.00	19970.000	0.000	46022.	0.000	4.311
4920.00	19970.000	0.000	46022.	0.000	4.311
4928.00	19970.000	0.000	46022.	0.000	4.311
4936.00	19970.000	0.000	46022.	0.000	4.311
4944.00	19970.000	0.000	46022.	0.000	4.311
4952.00	19970.000	0.000	46022.	0.000	4.311
4960.00	19970.000	0.000	46022.	0.000	4.311
4968.00	19970.000	0.000	46022.	0.000	4.311
4976.00	19970.000	0.000	46022.	0.000	4.311
4984.00	19970.000	0.000	46022.	0.000	4.311
4992.00	19970.000	0.000	46022.	0.000	4.311
5000.00	19970.000	0.000	46022.	0.000	4.311
5008.00	19970.000	0.000	46022.	0.000	4.311
5016.00	19970.000	0.000	46022.	0.000	4.311
5024.00	19970.000	0.000	46022.	0.000	4.311
5032.00	19970.000	0.000	46022.	0.000	4.311
5040.00	19970.000	0.000	46022.	0.000	4.311
5048.00	19970.000	0.000	46022.	0.000	4.311
5056.00	19970.000	0.000	46022.	0.000	4.311
5064.00	19970.000	0.000	46022.	0.000	4.311
5072.00	19970.000	0.000	46022.	0.000	4.311
5080.00	19970.000	0.000	46022.	0.000	4.311
5088.00	19970.000	0.000	46022.	0.000	4.311
5096.00	19970.000	0.000	46022.	0.000	4.311
5104.00	19970.000	0.000	46022.	0.000	4.311
5112.00	19970.000	0.000	46022.	0.000	4.311
5120.00	19970.000	0.000	46022.	0.000	4.311
5128.00	19970.000	0.000	46022.	0.000	4.311
5136.00	19970.000	0.000	46022.	0.000	4.311
5144.00	19970.000	0.000	46022.	0.000	4.311
5152.00	19970.000	0.000	46022.	0.000	4.311
5160.00	19970.000	0.000	46022.	0.000	4.311
5168.00	19970.000	0.000	46022.	0.000	4.311
5176.00	19970.000	0.000	46022.	0.000	4.311
5184.00	19970.000	0.000	46022.	0.000	4.311
5192.00	19970.000	0.000	46022.	0.000	4.311
5200.00	19970.000	0.000	46022.	0.000	4.311
5208.00	19970.000	0.000	46022.	0.000	4.311

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[illegible]

[illegible]

LIST OF CONTROL PARAMETERS FOR SEDSAT_REF39 (Last update May 15, 1995)

Here below is the complete list of the control parameters for SEDSAT control law SEDSAT_Ref39 as they stand before the characteristics of the new tether are measured and the deployment tests are carried out.

The values of the parameters for SEDS2 Ref1_14jun93 (the flight control law for SEDS2) are also shown to point out the differences wherever applicable.

----- CONTROL PARAMETERS -----					
No.	PARAMETER	TYPE	Units	SEDSAT	SEDS-II
1.	C	Filter Coefficient		0.125	0.125
2.	GTC	TurnCount Gain	(1/Turn)	0.002	0.002
3.	DZTC	TurnCount Deadzone	(Turn)	5	5
4.	TCELIM	Maximum Turn Count Error	(Turn)	5000	3000
5.	GTCR	TurnCount Rate Gain	(s/Turn)	0.2	0.2
6.	DZTCR	TurnCountRate Deadzone	(Turn/s)	0.5	0.5
7.	TCRELIM	Maximum Turn CountRate Error	(Turn/s)	10	5
8.	WAILP	Wrap Increment Upper Limit		2	1
9.	TBD s	Time after which Bias is applied	(s)	65535	65535
10.	BIAS	BrakePost Bias	(Turn)	0	0
11.	WACLP	WrapAdjustment Upper Limit	(Turn)	7	6
12.*	TCBS	Turn Count Brake Stop	(Turn)	46000**	45500
13.*	A1	Coeff_1 in Variable Gains		0.6980403	0.6980403
14.*	A2	Coeff_2 in Variable Gain		5.7380313E-6	5.7380313E-6
15.	STOPDEPLOY	Time from Ejection for Brake Ramping up	(s)	5000	6560

* These parameters are very likely to change for the new tether.

** Value updated on May 15, 1995.

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